1966

"Scoria" of North Dakota

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"SCORIA" OF NORTH DAKOTA

by

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B.S., M.S. in Geological Engineering,

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A Dissertation

Submitted to the Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the Degree of

Doctor of Philosophy

Grand Forks, North Dakota

January
1966

This dissertation submitted by Robert J. Sigsby in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in the University of North Dakota is hereby approved by the Committee under whom the work has been done.

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ACKNOWLEDGMENTS

The writer is indebted to the North Dakota Geological Survey for field and equipment expenses during the summers of 1962, 1963, and 1964. Additional expenses of reproduction in this paper were also defrayed by the same agency. Thanks are due to the National Park Staff of Theodore Roosevelt National Memorial Park for their cooperation during the field seasons. The people of Medora and the surrounding area are also to be thanked for the many courtesies extended during the three pleasant field seasons.

The writer wishes to thank the following persons for their aid in this study: Dr. W. M. Laird, State Geologist, Chairman of the Department and Chairman of the writer's committee, for defining the problem, offering suggestions, and critically reading the typescript. Dr. W. L. Moore, Dr. F. D. Holland, Jr., Dr. G. C. Wheeler, and Dr. R. A. Caldwell, members of the writer's committee, for offering useful suggestions, and critically reading the typescript. Prof. Holland for suggesting the problem and for suggestions on organization, philosophy, and style which improved the final version of this paper immensely. Dr. Laird, Dr. Moore, and Dr. Holland also visited the writer, individually and respectively, during the summer field seasons of 1962, 1963, and 1964. Rodney Feldmann, Charles Frye, and Chester Royse, doctoral candidates, for their many helpful discussions concerning stratigraphy and techniques. Prof. C. E. Mann for helping the writer with firing experiments leading to the formation of "scoria" analogs, and procurement of equipment. Miss Adalynn Magnusson, Technical Analyst in the Fuel Testing Laboratory, for numerous analyses of lignite and ash. Mr. Virgil Rogers, Ceramic Engineer at the Hebron Brick Co., for his information on the utilization of "scoria" in ceramics. Prof. D. P. Naismith of the Mechanical Engineering Dept. for his help in the construction of temperature measuring equipment, and for the loan from that department of a direct-reading potentiometer. Members of the North Dakota Highway Department for information on "scoria" outcrops, and the utilization of "scoria" as a lightweight aggregate. Finally, Constance Rigsby, the writer's wife, for typing the final version of this paper.

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"SCORIA" OF NORTH DAKOTA

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The University of North Dakota, 1966

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The rock commonly called "scoria" in North Dakota, which also occurs throughout much of the lignite-bearing area of the western United States, is produced by the metamorphism of overburden through the action of underlying burning lignite seams. The purpose of this study is to relate the physical, chemical, and mineralogic characteristics of lignite, parent sediments, and "scoria" to each other, and to investigate the occurrence, processes of formation, thermochemistry, chemical changes, petrography, topographic effects, structural geology, and economic geology of this metamorphic rock. This study represents the culmination of field investigation during three summers in western North Dakota, and particularily, near Medora, North Dakota.

The widespread occurrence of this metamorphic rock precludes the importance of incidental ignition of lignite by lightning, prairie fires, and the activities of man. The high volatility of the lignites, high summer temperatures, and a supply of moisture and iron sulfide make widespread and recurring spontaneous combustion a more likely

general cause of ignition.

The factors necessary for the formation of "scoria" are: a suitable grade and thickness of exposed lignite, ignition, and an alterable overburden. Measurement of temperatures in two burning lignite areas, however, indicates that the maximum measured temperature (803°C) is not sufficient to produce significant amounts of "scoria" in the present, simple oxidizing environment. Sedimentological, optical, chemical, and X-ray analysis of the sediments, and proximate analysis of the lignites in these two burning areas indicate that these sediments and lignites are not significantly different from those which have formed "scoria" in the past. "Scoria" analogs, produced by the firing of similar parent sediment samples, show that "scoria" could be produced from these sediments, and indicate the changes which take place with increasing temperature. It is concluded, therefore, given suitable lignite and sediments, that the formation of "scoria" is most dependent on the thickness of overburden. The thickness of the overburden must be great enough to sustain extended, air-restricting caverns in the burning lignite to produce significant amounts of "scoria". Thicker, and more strongly metamorphosed "scoria" is formed in a reducing and distilling environment. The minimal thickness of overburden necessary to form extensive "scoria" appears to be greater than 25 feet. Various combinations of conditions have lead to four modes of formation of "scoria" in the study area.

Geologically, the term scoria is a misnomer as applied to this metamorphic rock, but the name has been retained herein, in quotation marks, on its sole virtue, popular acceptance. Petrographic, chemical, and X-ray analysis indicate that "scoria" can be subdivided into nine varieties: baked shale, baked sandstone, baked limestone, baked sandstone, porcellanite, vitrified siltstone, vitrified laminated shale, glassy slag, and recrystallized slag.

Generalizations concerning proportionate lignite-ash-"scoria"-overburden relationships are generally valid only when burning occurred in an oxidizing environment. These relationships are more dependent on conditions of formation, than to directly proportionate thickness of lignite, ash, "scoria", and overburden.

The general effects of "scoria" on topography are the preservation of buttes and ridges capped by "scoria", and the retardation of erosion of slopes covered by "scoria" talus. Structural analysis of jointing in "scoria" indicates a general relationship between orientation of jointing and dissection, but pseudocolumnar jointing is controlled by orientation of the cooling surface. Pseudocolumnar jointing is mainly restricted to sandstone as a result of its higher content of quartz, which has unusual thermal expansion properties. The pseudocolumnar joint pattern, which deviates from the expected hexagonal pattern, is influenced by several factors.

Deposits of "scoria" are abundant and widespread, but discontinuous, and variable in composition and variety. Present application, and suggested uses indicate that the utilization of this resource has barely been explored.

This abstract of a dissertation submitted by Robert J. Sigsby in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in the University of North Dakota is hereby approved by the Committee under whom the work has been done.

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INTRODUCTION

The rock type commonly referred to as "scoria" or "clinker" in North Dakota and surrounding areas, is the product of burning lignite seams which have metamorphosed the overlying sediments and sedimentary rocks of Paleocene age. This material is common throughout much of the lignite-bearing area of the western United States, capping buttes and divides, and generally preserving the picturesque Little Missouri Badlands topography from erosion.

Metamorphism of the sediments is usually oxidizing in nature and produces the pastel red and yellow tints which arrest the eye throughout much of the Badlands region. In some cases however, the metamorphism proceeded in a reducing environment, to produce material which is generally darker in color, vesicular, and occasionally, glassy or slaggy in nature. Varieties of this melted material cannot be distinguished macroscopically from some coarse volcanic material. It is thus easy to understand why some early explorers and investigators attributed an igneous origin to specimens isolated from their source. The influence of this incorrect observation remains in the application of the geologically erroneous term "scoria" to non-igneous rock.

Although the general character and gross effects of this metamorphism have long been recognized, the variation in processes of formation, and in the resulting product have been but little studied. The most recent petrographic study, in the western lignite-bearing area, is that of Rogers' (1918) and it is this field of study which is particularly amenable to modern systematic investigation.

It is the purpose of this paper therefore, to relate the physical, chemical, and mineralogic characteristics of the lignite, parent sedimentary material and metamorphic equivalents to each other, and to investigate the occurrence, processes of formation, thermochemistry, chemical changes, petrography, topographic effects, structural geology, and economic geology of this fascinating metamorphic rock.

The general plan is to investigate the causes of burning of lignite, examine the composition of the parent sediments, produce "scoria" analogs from these sediments, investigate two presently burning areas, and then, from the collected data and observations, determine the conditions for formation of "scoria". The mode of "scoria" formation, varieties of "scoria" produced, and the lignite-ash-"scoria"-overburden relationships are then discussed, in the light of conditions of formation of "scoria". Within individual chapters, the usual order of presentation is: previous work, present investigation, and summary.

HISTORY OF STUDY

Early Investigation

Probably the first explorers to cross the area in which "scoria" is found were La Verendrye and his sons in 1738 but they did not record (Flandrau, 1925) the occurrence of baked sediments in any of their travels. Later, James Mackay in 1795 penetrated as far as the vicinity of present-day Bismarck (Holland, 1961, p. 46) but he also failed to note whether "scoria" had been encountered.

It remained then, for the explorers Meriwether Lewis and William Clark, while mapping the Missouri River in 1805, to make the first report on the occurrence of "scoria" in North Dakota. Besides surveying the course of the Missouri River they also made excellent biologic and geologic observations and recorded them in their journals in an exceptionally accurate, if less than completely literate, manner. Lewis and Clark had spent the winter of 1804-1805 at Fort Mandan north of the present-day North Dakota town of Mandan. As the weather broke in the spring, Clark began making short, exploratory trips in the vicinity of the fort. On March 21, 1805, he recorded in his journal (Reid, 1948; Devoto, 1953):

> Saw an emence quantity of Pumice Stone on the sides & foot of the hills and emence beds of Pumice Stone near the Tops of the[m], with evident marks of the Hills having once been on fire. I Collected Some [of] the different [sorts] i.e. Stone Pumice & a hard earth, and put them into a furnace, the hard earth melted and glazed the others two and the hard Clay became a pumice Stone Glazed.

Thus, even as he supervised preparations for the spring departure, the leader was making scientific observations on the geology of the area.

Shortly after leaving Fort Mandan on the 7th of April, near the present town of Riverdale, North Dakota, Lewis discussed the geology observed on that day (April 9):

> the hills of the river are very broken, and many of them have the appearance of having been on fire at some former period. Considerable quantities of pumice stone and lava appear in many parts of these hills where they are broken and washed Down by the rain and melting snow.

On the following day (April 10), just south of Old Fort Berthold, the voyagers noticed a bluff, about which Lewis wrote, "is now on fire and throws out considerable quantities of smoke which has a strong sulphurious smell." This appears to be the first record of a burning coal bed in North Dakota (Holland, 1961, p. 48).

They continued to record the occurrence of "pumice stone", "lava" and associated lignite on the 11th and 14th of April until, on the 16th, exposures near the present Mountrail-McKenzie county line led Lewis to speculate on the origin of the "pumice" and "lava".

> I believe it to be the stratas of coal seen in those hills which causes the fire and birnt appearances frequently met with in this quarter. where those birnt appearances are to be seen in the face of the river bluffs, the coal is seldom seen, and when you meet with it in the neighbourhood of the stratas of birnt earth, the coal appears to be presisely at the same hight, and is nearly of the same thickness, togeter with the sand and a sulphurious substance which usually accompanys it.

It would appear that the experiments of Clark, and the common conclusions of the two as to the origin of "scoria" antedated the erroneous "catastrophic" interpretations which captivated popular opinion for the next fifty years.

It is probable that the occurrence of "burned stones" recorded by Francois Antoine Larocque in his journal (Haslitt, 1934, p. 11) on July 11, 1805 also referred to "scoria". While exploring east of the Little Missouri River, apparently in the Medora, North Dakota area, he recorded:

> We have crossed a chain of mountains of a width of nearly 3 miles and on their summits lies a pile of stones which appear to have been burned; a part of the rock broke off from the mountains.

The next significant records were those left by the artist George Catlin who, in 1832, was on the first steamboat to reach the Yellowstone River (Holland, 1961, p. 49). Catlin painted the "pumice stone" buttes and described them in terms of an artist. On his voyage down-river from the mouth of the Yellowstone he observed bluffs near the Mandan Village and commented (Catlin, 1913, p. 78) that:

> To this group of clay bluffs, which line the river for many miles in distance, the voyageurs have very appropriately given the name of "the Brick-kilns;" owing to their red appearance, which may be discovered in a clear day at the distance of many leagues.

He further observed (p. 79):

> . . . that the superstratum, forming the tops of these mounds (where they remain high enough to support anything of the original surface) is composed, for the depth of fifteen feet of red pumice; terminating at its bottom, in a layer of several feet of sedimentary deposit, which is formed into endless conglomerates of basaltic crystals.
>
> This strange feature in the country arrests the eye of a traveller suddenly, and as instantly brings him to the conclusion, that he stands in the midst of the ruins of an extinguished volcano.

Although Catlin's observations on badland erosion were very modern, his erroneous "conclusion" as to the volcanic origin of "scoria" influenced investigators for some time.

Alexander Philip Maximilian, Prince of Wied-Neuwied arrived at Fort Clark (near the present town of Stanton, North Dakota) on June 18, 1833 (Thwaites, 1905, p. 338). He was, perhaps, the most astute scientist and observer to have visited the Upper Missouri up to that time. On the 25th of May, while at Cedar Fort near Rosebud Creek, (South Dakota) he observed (Thwaites, 1905, p. 302-303):

> Directly opposite, (Cedar Fort) on the east bank, a stratum of earth burnt till 1823, in consequence of which a large portion of hill fell, and now stands isolated before the bank; it is seventy or eighty feet high, and 150 feet long.

On the 7th of June north of Fort Pierre (South Dakota), he recorded (p. 331):

> The earth and stones everywhere indicated that they had undergone change by fire. The earth was hard, friable, with many crevices -- the stones brown, blackish, and often looking like scoria.

Maximilian also wrote (Thwaites, 1905, p. 212) of his observations on November 3, 1833, of "scoria" above the site of Fort Clark and the subsequent regrettable loss of his extensive geological collections (in the burning of the steamboat "Assiniboine" near present-day Bismarck, June 1, 1835; vide Thwaites, 1905, p. 240):

> I increased my collections with the most interesting series of the rocks of the Upper Missouri, which, I regret to say have not reached Europe, as they were irrecoverably lost. On this voyage down the river I had better opportunities of examining the singular red, burnt, and conical tops of the summits of the bank, and they afforded me much interest. The rocky walls, and the red hills, covered with fragments burnt red, exactly resembled the refuse of our brick kilns, and they emitted, when struck, a clear sound, like that of the best Dutch clinkers. Under those red cones we generally saw a stratum of the bituminous coal; both often appeared together.

Finally, from observations made in the vicinity of Fort Clark, he wrote (p. 212):

> In many places it may be evidently seen that these strata have

> been on fire. The surrounding clay is frequently burnt red, and the shards are perfectly coloured, hard and sonorous, like our bricks and Dutch clinkers. About Fort Clarke they know nothing of such fires, but they have frequently occurred lower down the Missouri. The red clay, which we have so often spoken of, appears to have been elevated by the action of fire. On the banks, extremely light, porous, cellular, red brown scoriae are everywhere found, which the people here call pumice stone, though they are totally different from the fossil usually so called, and of which extensive strata are found on the banks of the Rhine.

It is apparent that Maximilian recognized the relationship between the burning coal seams and the pyrometamorphosed sediments, but his insistence upon their "elevation by the action of fire" would appear to imply also a belief in related vulcanism. Still, he recognized the difference between the "scoriae" of the Dakotas and the igneous rock of the Rhine Valley.

Jean Nicholas Nicollet and John C. Fremont entered the "Upper Missouri Country" soon (1839) after Catlin, and Nicollet (1843a, p. 154-155) read a paper on the geology of the area before the Association of American Geologists and Naturalists on the 28th of April 1843. A report of this meeting reads in part:

> In the midst of the clay banks, and from the summit of the hills, dense smoke is frequently observed to arise from crevices in the plastic clay; he [Nicollet] called them pseudo-volcanoes. From this fact, and from the occurrence of the light spongy material brought down by the waters, and strewed along the shore, many have erroneously supposed that volcanoes existed on the Upper Missouri. This, however, is a mistake. . . . The Indians call these spots _mankah mite_, or 'smoking earth' — thus recognising their difference from volcanoes, which would be called burning mountains.

Nicollet reported confidently, although his writings indicate that he never saw a burning lignite seam but was relying on reports of Indians and voyageurs.

At this meeting, and in a fuller report published later in that year, Nicollet (1843b, p. 39) commended Catlin on his depiction of "the pictorial features of this country" but went on to emphasize:

> There are, however, no <u>true</u> volcanoes over any portion of the United States east of the Rocky Mountains; and it was this belief that led me to the adoption of the word <u>pseudo-volcano</u>. Neither is the substance found in these regions, and commonly called pumice, a true pumice; and, by similar analogy to that which has prompted the name of its probable origin, I have called it a <u>pumiciform</u> stone, (<u>roche pumiciforme</u>.)

Nicollet further (p. 40) applied a mineralogical name to the fine grained, less slaggy varieties of "scoria" and clearly stated his views of the origin of "pseudo-volcanoes":

> Layers of the clay are also met with, so altered as almost to deserve the mineralogical name of porcellanite; in fact, all the minerals belonging to the formation exhibit the alteration which might be supposed produced by exposure to that sort of action now to be assigned.
>
> I believe, and it is also the opinion of my friend Professor Ducatel, to whom I submitted my specimens, that these pseudo-volcanic phenomena may be compared with those described as occurring in other portions of the globe, under the name of <u>terrains ardens</u>; although they are not here accompanied by the emission of flames. They are evidently due to the decomposition, by the percolation of atmospheric waters to them, of beds of pyrites, which, reacting on the combustible materials, such as lignites and other substances of a vegetable nature in their vicinity, give rise to a spontaneous combustion; whilst further reactions (well understood by the chemist) upon the lime contained in the clay bed, produce the masses and crystals of selenite that are observed in the lower portion of this interesting deposite. This is the theory which, with some little confidence, we have formed of these pseudo-volcanoes.

Nicollet also (p. 41) ascribed the Badlands to his "pseudo-volcanoes".

> The name of "Mauvaises Terres" (bad lands) has been applied to districts cut up into deep and intricate chasms, from which the traveller could hardly hope to extricate himself without the assistance of a good guide, and that are doubtless due to the burning out of their pseudo-volcanoes.

John James Audubon led a party up the Missouri to study the quadrupeds of North America during the summer of 1843. Accompanying his were John G. Bell and geologically-inclined Edward Harris (Holland, 1961, p. 51). Audubon's observations were mostly biologic, but on a trip into the Badlands he observed "scoria" and remarked (Audubon and Coues, 1898, p. 149), "This whole is evidently the effect of volcanic action. . ." He continued (p. 152):

> Whether my theory be correct or incorrect, it is this: These hills were at first composed of the clays that I have mentioned, mingled with an immense quantity of combustible material, such as coal, sulphur, bitumen, etc.: these have been destroyed by fire, or (at least the greater part) by volcanic action, as to this day, on the Black Hills and in the hills near where I have been, fire still exists; and from the immense quantities of pumice stone and melted ores found among the hills, even were there no fire now to be seen, no one can doubt that it had, at some date or other, been there; as soon as this process had ceased, the rains washed out the loose material, and carried it to the rivers, leaving the more solid parts as we now find them; the action of water to this day continues.

Somewhat earlier, Bell had left the group to undertake an extensive trip through the Little Missouri Badlands (Audubon and Coues, 1898, p. 176). On returning, (August 2, 1843) he commented on burning lignite seen in the vicinity of Fort Union (near modern Williston, North Dakota) saying:

> We saw hills impregnated with sulphur and coal, some of them on fire, and now and then portions of them gave way, by hundreds of tons at a time. In one place I saw a vein of coal on fire; . . . It was burning very slowly, and in several places, for about fifty yards, emitting whitish smoke, something like sulphur when burning, and turning the earth or rock above, quite red, or of a brick color. It would undermine the earth above, which then fell in large masses, and this was the cause of the obstruction in the path before us. . . . Where the fire was burning, the clay was red, varying from one to three feet in thickness; no appearance of coal presented itself where the fire had passed along and was extinguished, but very distinct above the fire, . . .

His account (McDermott, 1951, p. 173) convinced Harris that ". . . neither in the recently or more anciently burnt portions is there the least appearance of <u>Pumice Stone</u> as stated so confidently by Catlin. . . ." Harris also wrote (McDermott, 1951, p. 177) on August 24, 1843, of finding ". . . Red Stones with impressions of leaves as as petrified wood." Thus he recorded the first find of fossils in "scoria".

Edward Harris published his account of the Audubon trip in the Proceedings of the Academy of Natural Sciences of Philadelphia in May, 1845. He stated that he could find no volcanic matter in the Mauvaises Terres and that (p. 237):

> The red appearance of the shale and clay, and in many instances of the sandstone, is, I believe, to be attributed to the action of fire, but may be more readily accounted for from the effects of the spontaneous combustion of the coal going on at the present day, than from volcanic agency. These evidences of fire, occur in so many of the strata at such different levels, that to give them the latter origin we are compelled to suppose a succession of eruptions, but in this case what has become of the tuffa and lava?

Harris sent some specimens of leaf impressions to the Academy, which he said (p. 237-238) were ". . . evidently changed in their specific gravity by the action of fire, and your Committee will be better able than myself to judge, whether an increase of the heat, short of that necessary to produce vitrification, may not have converted the mass into the red pumice of the Missouri."

The committee (Rogers, Morton, and Johnson, 1845, p. 239), appointed by the Academy to study the specimens collected by Harris found:

> From the evidence afforded by the series of specimens it is clear that the so-called Pumice is not a true volcanic product, but is originally an argillaceous sandstone, probably a <u>lacustrine</u> deposition of a tertiary age.
>
> *
>
> . . . the material offers the most unequivocal marks of being derived from the spontaneous combustion of a sedimentary argillo-arenaceous stratum. The rock is seen in almost every

state of gradation from a stratified mass containing beautifully distinct impressions of leaves of terrestrial trees, to a light vesicular pumice. Certain half-fused specimens show indeed the well preserved traces of these leaves, the partially melted condition and the nearly perfect vesicular structure, all upon the same mass.

They concluded (p. 239):

This explanation of the origin of the pumice [Harris's], sustained as it is by the drawings and descriptions of the scenery given by the Prince Maximilian, and borne out by the fact that no other material, of even an imputed volcanic source, has ever been discovered in the plains of the Missouri, renders it highly probable that the stratified pumice, alledged by Mr. Catlin to exist there, is derived from the same cause.

Survey and Society Investigations

The "Upper Missouri Country" experienced a great expansion of scientific traffic during the 1850's with the advent of vast land surveys by the Federal Government and increased interest in the newly "opened" lands by scientific societies.

One of the first surveys to mention the occurrence of "scoria" in any detail was that led by Dr. F. V. Hayden in 1859. Hayden appeared to discern the true nature of "scoria" in the area between the Rosebud and Tongue Rivers in present-day Montana. In discussing the valley of the Rosebud River, he said (p. 56):

. . . we encountered the same rugged country, with indications of the burning out of the lignite beds and the fused and semi-fused material covering the hills, giving them a peculiarly picturesque, reddened appearance.

Speaking of the divide between the two rivers nearer the mountains, he said: "The summits of the ridge present a beautiful red appearance from the burning out of lignite beds."

Dr. C. M. Hines, another member of the 1859 Hayden Expedition, observed that along the right bank of the Rosebud, ". . . the surface of the hills . . . [was] covered with broken and detached pieces of stone and burnt clay to the depth of forty or fifty feet."

Hines seems to have been the first to describe the burning lignite along the Powder River. It was from "the sulphurous vapors rising from the burning beds of lignite" that the river apparently derived its name (according to Gen. W. F. Raynolds, military leader of the Hayden expedition). Hines (1869, p. 96) said:

> Eight miles below our yesterday's camp we discovered the stratum coal (lignite) on fire. Considerable smoke issued therefrom, having a strong sulphurous smell. The heat at this point was so intense that we could not stand within twenty feet from whence the smoke issued. A thick layer of sandstone laying immediately above it, four feet, was completely calcined. From this point, at the same elevation, to some distance below the mouth of Clear Fork, I noticed the same red color given to the banks by the burning out of the coal bed. Here and there were portions that had escaped. The origin of the fire I was unable to account for, unless it contains within itself the elements of spontaneous combustion.

The tendency to revert to volcanic fires when searching for a source of heat capable of producing baked and melted shale and slag was not confined to the "Upper Missouri Country". In 1857, while a member of the Pacific Railroad Survey, Thomas Antisell attributed similarly metamorphosed Monterey Shale to volcanic processes (in Arnold and Anderson, 1907). Concerning the foothills of the Santa Ynez Mountains a few miles east of Santa Barbara, California, he wrote:

> In this part of the chain the volcanic forces cannot be said to be quiescent as yet. On Dr. Hobbin's ranch . . . occasionally fire, smoke, and sulphurous vapor has been emitted, from fissures in the rock, in large quantities within a few years past. A similar volcanic vent exists at Rincon.

The metamorphic process here is different only in that the fuel is oil in the Monterey Shale, rather than lignite.

Probably the fullest and best description of "scoria" during this period was provided by J. A. Allen from observations made in the summer of 1873, while attached as zoologist to the North Pacific Railroad Expedition. Allen noted the relationship between stratification of parent sediment types and the resulting metamorphic product. He also recognized that the ash and cinder-like products were the residium of burning coal veins and that the thickness of these products and the "scoria" was proportional to the original thickness of the veins. Further, he recognized that some of the outcrops had experienced metamorphism beyond that expected from simple burning and theorized that these "chimney-like" brecciated masses were caused by explosive gases. The origin of the fires puzzled Allen; for he suspected that they had "more than a single cause". Although he knew of several validated cases of ignition by prairie fires, he tended to concur with the spontaneous combustion theories of Nicollet and Hines. His investigations, and particularly his detailed descriptions, remained the outstanding work on these baked sediments of the "Upper Missouri Country" for the next thirty years.

In 1883, C. A. White investigated the burning lignites in the "Laramide Group" while employed by the United States Geological Survey. He traced lignite beds into local ash beds underlying the "scoria" and convinced himself that the majority of the fires were caused by spontaneous combustion. White also speculated on the time at which the earliest burning took place. He concluded (White, 1883, p. 26) that the isolated slag masses resting on knolls represented old horizons "let down" by long-continued erosion and that the fires which metamorphosed these sediments might have "occurred as early as, if not earlier than, later Tertiary time."

In the same year, T. H. McBride (1883, p. 469) described many of the features of the "Missouri Bad Lands", particularly the "diversity of form and color" provided by baked sediments. He diagramed a cross section of a burning lignite seam and illustrated the faulting and collapse of the overlying sediments resulting from caverns left by the burned-out lignite. Water ascending into the fractures and the resulting escaping steam led McBride to suspect that this might be the mechanism by which locally intense metamorphism was accomplished. McBride did not, however, consider that these metamorphic processes of the Badlands could long survive, due to the decreasing amount of lignite exposure.

It is perhaps worth mentioning that Theodore Roosevelt also wrote about the occurrence of "scoria" in the North Dakota Badlands in <u>Hunting Trips of a Ranchman</u>, published in 1885. Although it is clear that he understood the relationship between burning lignite seams and the baked, brick-like products, his reference to "volcanic rocks" is somewhat puzzling. It would appear that he may have attributed the more strongly metamorphosed material to volcanic action.

Recent Investigators

Ferdinand Zirkel was one of the first to apply microscopy to the study of "scoria". He described, petrographically, specimens gathered from the United States and from European coal fields in his <u>Lehrbuch der Petrographie</u> in 1894 (p. 775-776). He also suggested the terms <u>Porzellanit</u> and <u>Porzellanjaspis</u> for varieties of "scoria". J. E. Hibsch has also described slag-like material from the Mittelgebirges (northern Bohemia) under the name Kohlenbrandgesteine (Rogers, 1918, p. 8).

During the next fifteen years a number of authors mentioned the occurrence of "scoria" and its formation. E. S. Bastin (1905) noted the similarity between baked clays and natural slags in eastern Wyoming and those in the Coal Measures near La Salle, Illinois, and in the European coal fields. He also investigated the mineralogy of some "scoria" specimens.

In 1907, Ralph Arnold and Robert Anderson recorded the occurrence of similar metamorphic processes in several regions of bituminous rocks in California. Although the fuel in this case is petroleum, the metamorphic rocks are apparently analogous to those of the Little Missouri Badlands. In this publication, the authors investigated the history, occurrence, lithologic character, and depth of penetration of burnt shale in the Monterey Shale of Santa Barbara County.

A. G. Leonard, during his term as State Geologist of North Dakota, wrote extensively on lignite in North Dakota and published numerous articles describing "scoria" (or "clinker" as he preferred to call it) both alone and in collaboration with others (1908, 1916, 1925, 1926, 1933). During the last summer of Dr. Leonard's life, reports of smoke rising from cavities on Black Butte in southwestern North Dakota had given rise to a rather widespread belief that this butte was of volcanic origin. Thus in his last paper, published posthumously, Dr. Leonard explained the flat-topped nature of Black Butte, its geologic setting and the origin of "scoria"; he said in part (p. 161-162):

> It is the presence of this clinker, or scoria, capping the conical buttes which has doubtless given rise to the belief that these buttes are of volcanic origin. . . . There is no

evidence that there have ever been any volcanoes in North Dakota, and it is certain that there are none today.

In 1915, Alexander Bowie wrote an article concerning the burning of coal beds in place in the southwestern states. He confined himself almost exclusively, however, to the penetration of the phenomenon, and the changes which took place in the character of the coal.

The most comprehensive investigation of "scoria" was that undertaken by G. S. Rogers in 1918 while employed by the United States Geological Survey. Rogers studied the causes of lignite combustion, general effects of burning, the petrographic character of the rocks formed and the resulting chemical changes. His professional paper stands as the pre-eminent work on these topics.

The term, clinkertill, introduced by L. P. Dove in 1922, is apparently an exact synonym of "scoria" or "clinker". Dove also commented (Leonard and others, 1925, p. 21-22) on the relationship between the thickness of "scoria" produced from a given thickness of lignite.

J. T. Lonsdale and D. J. Crawford in 1928 published a detailed investigation of a small outcrop of baked shale and "pseudo-igneous" rock of Tertiary age located in Freestone County, Texas. Their report followed much the same pattern as that of Rogers.

C. J. Hares' investigation of lignite in southwestern North Dakota, published in 1928, mentioned and described the occurrence of porcellanite and clinker in the Marmarth Field. His work physically correlated the lignites and "scorias" in that area.

In 1937, H. D. MacGinitie observed that the burning of coal had produced a rock which resembled, superficially, an effusive volcanic rock, near Hyampom, California (Lydon, 1964, p. 104).

The short article by P. R. May in 1954 clarified the principles of "clinker" formation introduced earlier by Allen and Rogers. This was followed in 1955 by W. S. Elain's resume of "scoria" in North Dakota.

One of the unusual features formed in connection with burning lignite beds is the columnar jointing in metamorphosed sandstone overlying the burned out area. Apparently Allen was the first to describe this "prismatic structure" (1874, p. 251). W. M. Laird, present State Geologist of North Dakota, coined (1950, p. 14) the term "pseudo-columnar jointing" for this phenomenon described from his investigation of "scoria" in the South Unit of Theodore Roosevelt National Memorial Park. D. L. Blackstone has also commented (1963) on an occurrence of columnar jointing in metamorphosed sandstone in Wyoming, a phenomenon which he considered unique in American scientific literature.

Two articles have recently (1964) appeared by P. A. Lydon concerning "silicate slag" from Trinity County, California, which apparently has the same type of origin as "scoria" in North Dakota.

Publications by Sigsby and Holland (1964) and by Sigsby (1965) have discussed, respectively, the history of the term "scoria", and the present lack of "scoria" in two burning lignite areas in North Dakota.

Most papers on lignite deposits in western North Dakota and adjacent areas mention "scoria" and give specific examples of unusual occurrences (e. g., Kepferle and Culbertson, 1955).

Many publications of the North Dakota Geological Survey also mention the occurrence and formation of "scoria". However, a history of this type is, of necessity, too short to include all cursory references to "scoria".

OCCURRENCE OF "SCORIA"

The formation of "scoria" is apparently not unique to any part of the world. In fact, metamorphosed rock of this nature has formed in many areas where the four basic factors of formation, (1) alterable sediments, (2) moderately to highly volatile fuel, (3) exposure, and (4) an agency of ignition, are present. Various authors have reported the occurrence of these unusual rocks in Germany, Bohemia, France, England, Canada and the United States (Allen, 1874; Rogers, 1918).

In the United States, rock formed by this metamorphic process has been recorded from the combustion of both lignite and petroleum in California (Arnold and Anderson, 1907; Lydon, 1964), and from the burning of lignite in Utah, New Mexico, Colorado (Bowie, 1915), Texas (Lonsdale and Crawford, 1928), Montana, Wyoming, North Dakota, South Dakota, Illinois (Bastin, 1905), and Pennsylvania (Allen, 1874).

The phenomenon of "scoria" formation has been found to be associated with moderately to highly volatile fuels, and therefore, the occurrence of "scoria" in areas of anthracite and low-volatile bituminous coal would be expected to be rare. The restriction of "scoria" formation to areas of moderately to highly volatile fuels is due to the greater susceptibility of these fuels to spontaneous combustion, which the writer believes to be the main cause of ignition. It is probable, however, that mining activity, and other agencies caused ignition leading to the formation of localized "scoria", in rare instances, by the burning of low-volatile fuels.

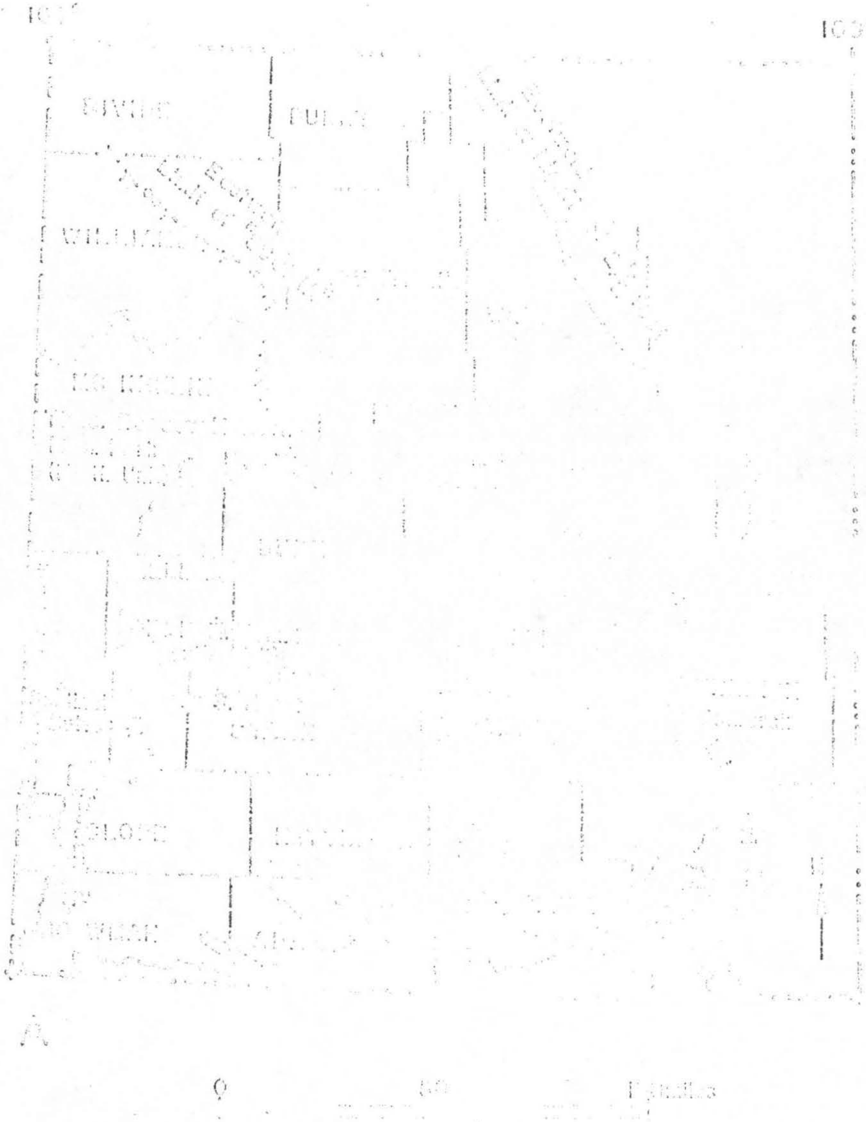
According to Rogers (1918, p. 1), burning of coal beds is a characteristic phenomenon throughout more than 200,000 square miles in the coal-bearing areas of the western United States. In North Dakota, Brant (1963, p. 1) has stated that the lignite field covers about 32,000 square miles in approximately the western half of the state. "Scoria" occurs, however, in less than half of this area (Fig. 1). It is also significant, for reasons to be discussed later, that the area of "scoria" formation is generally one typified by lignites having a thickness of two and one-half feet or more.

During the summer field seasons of 1962 and 1963, the writer attempted to determine the eastern limit of "scoria" by traveling westward along many of the major roads in western North Dakota. The combination of this investigation with research into numerous lignite reports has permitted the writer to draw the "scoria line" shown on Figure 1 which represents the eastern limit of "scoria" in North Dakota. It is possible, however, from the very nature of "scoria" formation, that some isolated, local patches may exist to the east of this line (e. g., the "scoria" in eastern Ward County, Fig. 1).

The greatest development of "scoria" is along the Little Missouri River and its tributaries in McKenzie, Billings, Golden Valley, Slope, and Bowman Counties. A somewhat isolated, but well developed area of "scoria" also occurs in Mercer, Stark and Morton Counties, particularly in the Glen Ullin-Hebron and Hazen areas. The White River and Golden Valley Formations, which usually do not contain "scoria", cover much of southwestern Stark County. "Scoria" also occurs only sparsely over large areas in eastern Slope, Hettinger, Bowman, Adams and Grant

Fig. 1A.—Location map showing the limits of the principal "scoria" outcrops and lignite in North Dakota (adapted from Brant, 1953).

Fig. 1B.—Portion of the North Dakota stratigraphic column as currently recognized by the North Dakota Geological Survey.



A

Systems	Rock Units		Lithologic Descriptions
	WHITE RIVER Fm. (Oligocene)		[illegible]
	GOLDEN VALLEY Fm. (Eocene)		0-200' Clay, sandy, [illegible]
	FORT UNION GROUP	Sentinel Butte Mbr.	Dark-gray bentonitic clay-stone and sh.; buff to brn. ss. Lignite.
			HT Butte Lignite "Facies"
Tertiary	TONGUE RIVER Fm.		Sh., [illegible] lt. to dark color [illegible]; lignite [illegible]
	LUDLOW Fm.		[illegible] clays and sh.
Cretaceous	HELL CREEK Fm.		0-575' Ss., sh., bentonitic clay; thin-bedded lignite.

B

Counties. Most of the "scoria" within these areas is further restricted to badlands or other markedly dissected topography.

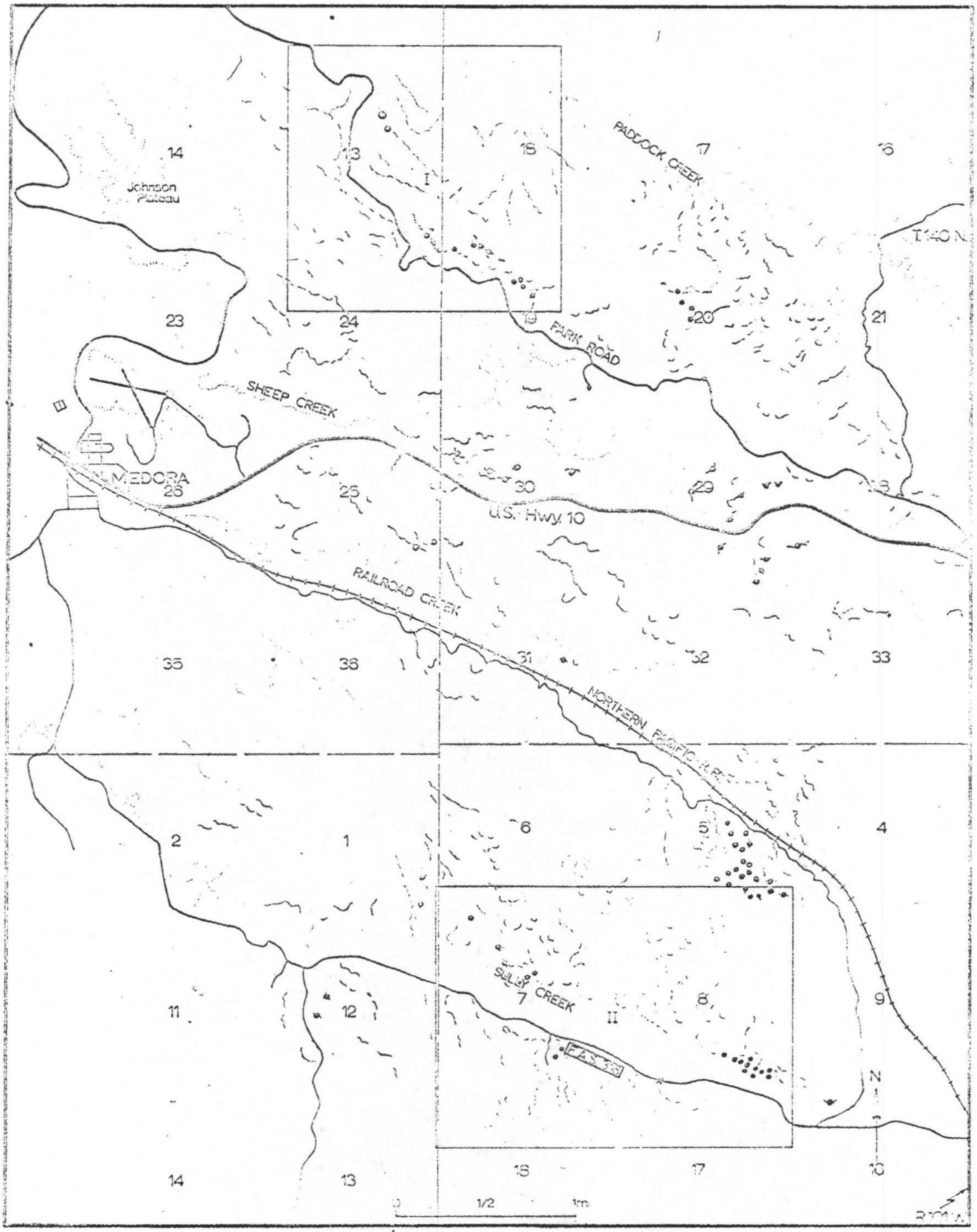
AREA OF STUDY

Location

On the advice of Dr. Wilson M. Laird, Chairman of the Department of Geology, University of North Dakota and State Geologist, the area around Medora, North Dakota, was used as a base of operations for the study of "scoria". Medora is located in Billings County, in the heart of the Little Missouri Badlands (Fig. 1). Initially, during the summer field season of 1962, more than a month was spent in a general reconnaissance of Billings, Golden Valley and Stark Counties to learn the general characteristics of the area, of "scoria" deposits, and of "scoria" formation. Lesser amounts of time were also spent during the field season of 1963 in general reconnaissance in the Glen Ullin-Hebron area, in Slope and Bowman Counties, and in visiting "scoria" sites near Sidney, Glendive, and Miles City, Montana.

From the experience gained in 1962, and a review of the collected data, the area immediately surrounding Medora, particularly that lying to the north and south of Medora along the Little Missouri River for seven miles in each direction, and east of the river for five miles was selected for further study (Fig. 2). This area is particularly amenable to study as a result of the good accessibility (for the Badlands), and for the extensive development and exposure of the "scoria" in the Tongue River Formation. Within this area, two more limited areas, were selected for intensive study. The first of these lies wholly

Fig. 2.—Location map of area of study. Drainage pattern emphasizes trend of ridges in area. "Scoria" outcrops are designated by short, wavy lines. "Chimney" locations are designated by large dots on short, wavy lines. Outlined areas I and II show limits of intensively studied areas which are shown in greater detail in Fig. 3 and 4, respectively.



14
Johnson Plateau
13
18
17
16
PADDOCK CREEK
I
T.140 N.
23
24
19
FARK ROAD
20
21
SHEEP CREEK
MEDORA
26
25
30
29
U.S. Hwy. 10
RAILROAD CREEK
35
36
31
32
33
NORTHERN PACIFIC R.R.
2
1
6
5
4
11
12
7
SULLY CREEK
II
8
9
F.A.S. 33
N
14
13
18
17
10
0
1/2
1m

within the South Unit of Theodore Roosevelt National Memorial Park and is centered around the middle section of the northwest-trending, park road (Figs. 1, 2, and 3). The second area lies southeast of Medora along Sully Creek (Figs. 1, 2, and 4). Both areas were chosen because they include continuous exposures of "persistent scoria" which incorporate most of the characteristics and variations typical of "scoria".

Numbers on mapped areas of intensive study (Figs. 3 and 4) designate the location of both measured sections and collected specimens and are referred to throughout the text. In addition, grab samples of Tongue River Formation sediments were collected from the following locations: (1) in the northwestern part of the South Unit, Theodore Roosevelt National Memorial Park, sec. 33, T. 141 N., R. 102 W. (NW Park); (2) at the Buck Hill Burning Coal Seam, sec. 23, T. 140 N., R. 101 W. (Buck Hill); (3) near South Heart, North Dakota, sec. 12, T. 139 N., R. 96 W. (South Heart); (4) near Hebron, North Dakota, sec. 21, T. 139 N., R. 90 W. (Hebron); and (5) at the top of the HT Butte Lignite, sec. 13, T. 140 N., R. 102 W. (locations may be found on Figs. 1, 2, 3, and 7).

Physiography

The "scoria"-bearing area of North Dakota lies within the Great Plains Province and mainly in the western part of the Missouri Plateau in North Dakota. This gently rolling plain slopes eastward towards the Missouri River. The part of this area commonly referred to as the Missouri Slope is a gently sloping plain interrupted by numerous buttes which rise 400 to 700 feet above the general surface, and by the badlands along the Little Missouri River. Dissection along other

Fig. 3.—Map of area of intensive study (Area I) located in township 140 north and ranges 101 and 102 west, Theodore Roosevelt National Memorial Park, Billings County, North Dakota. Drainage pattern emphasizes the location of ridges. Section and specimen locations are indicated by numbers ranging from zero to 99. "Scoria" outcrops are designated by short, wavy lines. "Chimney" locations are designated by large dots on short, wavy lines. Long, straight lines connecting locations indicate lines of sections referred to in text. Map from United States Department of Agriculture aerial photographs.

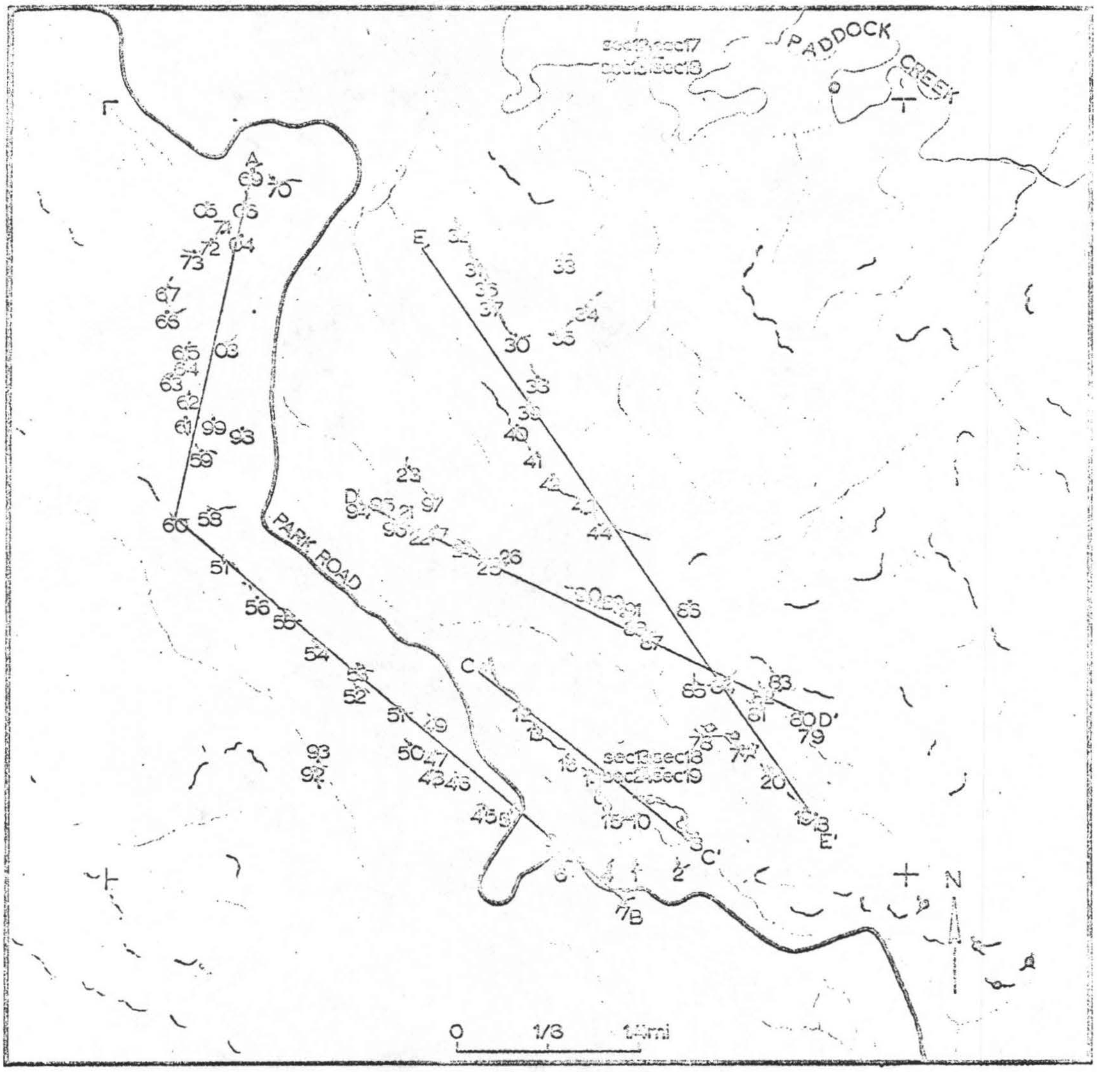
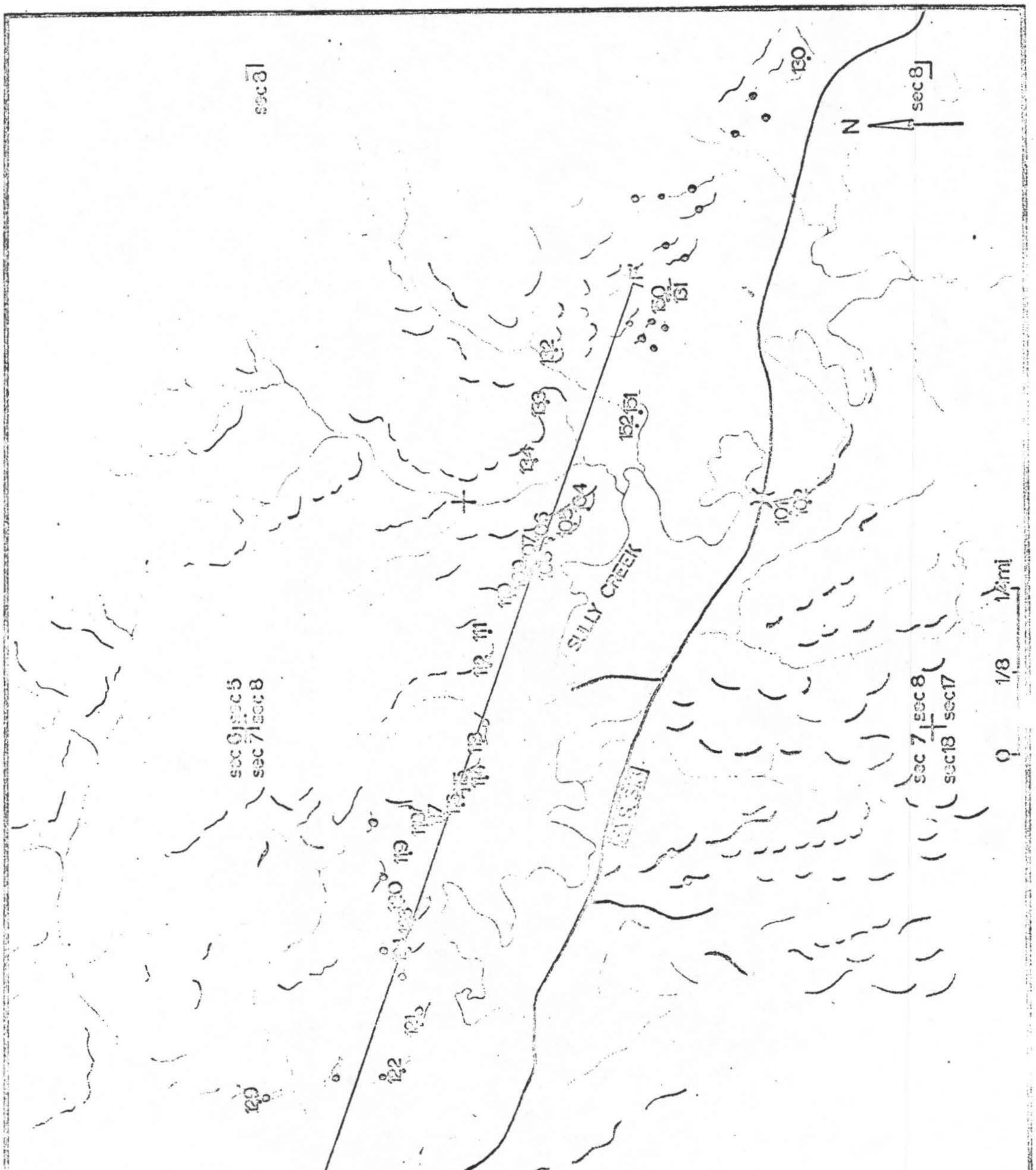

PADDOCK CREEK
PARK ROAD
N
0 1/3 1/4mi

Fig. 4.—Map of area of intensive study (Area II) located in township 139 north and range 101 west, about four miles southeast of Medora, Billings County, North Dakota, and about four miles south of Area I. Drainage pattern emphasizes the location of ridges. Section and specimen locations are indicated by numbers from 100 to 152. "Scoria" outcrops are designated by short, wavy lines. "Chimney" locations are designated by large dots on short, wavy lines. Line F - F' locates line of sections referred to in text. Map from United States Department of Agriculture aerial photographs.


SULLY CREEK
N
sec 8
sec 31
sec 6 sec 5
sec 7 sec 8
sec 7 sec 8
sec 18 sec 17
0
1/8
1/4 mi
F

major streams has also produced, locally, steep and rugged topography. The highest altitudes are in Slope and Bowman Counties in the southwestern part of the state, where the land surface is approximately 3,000 feet above sea level. White Butte in Slope County rises to an elevation of 3,506 feet, the highest point in North Dakota.

The most significant topographic feature, with respect to the formation of "scoria", are the badlands which are best developed along the Little Missouri River in the western one-third of the "scoria" area. This topography is formed both by headward stream erosion and sheet wash. The limited (approximately 15 inch annual average) rainfall is concentrated in short storms, and the resulting rain water immediately runs off the bare, only slightly permeable surfaces, in erosive streams to the stream channels. As a result, the slopes are eroded by tiny rivulets which channel, vertically and laterally, the butte slope. These channels eventually meet laterally, separating as a projection, the divide between rivulets from the main slope. In this manner, the butte is reduced in size but the butte side retains a relatively constant slope angle.

At least five levels of erosion, deposition, and a combination of deposition and erosion are visible along the Little Missouri River (Laird, 1950; Schmitz, 1955; Petter, 1956). Study of these terraces had revealed that the river originally flowed north from its easterly bend through a drainage system which emptied into Hudson Bay. According to Schmitz (1955), the development of badlands along the Little Missouri River began with the eastward diversion of the river and the lowering of its base level. Recent work by Tuthill and Laird (personal communication, 1965), however, indicates that probably only the upper level represents a still stand in the erosion cycle along the Little Missouri River and that the other levels represent cut terraces that were formed when the stream was down-cutting, as it still is.

Stratigraphy

The bedrock exposed in the "scoria"-bearing region of North Dakota range in age from Late Cretaceous to Oligocene (Fig. 1A). The Hell Creek Formation is the oldest bed in this region, but according to C. I. Frye (personal communication, 1965), who is presently completing a dissertation on the Hell Creek, the burning of lignites in this formation has not produced any "scoria".

The Fort Union Group, which contains most of the lignite in North Dakota, directly overlies the Hell Creek Formation. The group, as recognized by the North Dakota Geological Survey, from bottom to top, consists of the Ludlow Formation, which grades laterally eastward into the Cannonball Formation, and the Tongue River Formation. The Tongue River Formation is divided into a lower unnamed member and the upper, Sentinel Butte Member. The Tullock Formation may also extend into the Fort Union Group in North Dakota. The Fort Union Group is Paleocene in age. The United States Geological Survey, however, recognizes the Fort Union as a formation consisting of the members lying between the top of the Hell Creek Formation and the base of the Golden Valley Formation (Brown, 1962, p. 11-12).

The youngest beds, which overlie the Fort Union Group in buttes and mesas in the southeastern part of the "scoria"-bearing region, are the Golden Valley Formation of Eocene age and the White River Formation of Oligocene age. The White River Formation contains no lignite, but according to Benson and Laird (1947, p. 1166) the Golden Valley Formation does contain small quantities of lignite. To the best of the writer's knowledge, however, burning of lignite in this formation has produced little "scoria". Only stratigraphic units of the Fort Union Group are briefly discussed.

<u>Fort Union Group</u>

The Fort Union Group was named by Meek and Hayden in 1862 for exposures at Old Fort Union, near the mouth of the Yellowstone River, later called Fort Buford and now the town of Buford, North Dakota (Wilmarth, 1957, p. 762). While considered to be partly of Eocene age in some areas, the Fort Union Group in North Dakota is entirely Paleocene in age (Benson and Laird, 1947, p. 1166).

Ludlow Formation

Lloyd and Hares in 1915 named the Ludlow for non-marine rocks near Ludlow, South Dakota, which interfinger with those of the Cannonball Formation. This formation is equivalent to the Tullock and Lebo Shale Member of southeastern Montana. In the area of investigation, the outcrop of the Ludlow is limited to a band less than ten miles wide that extends southeasterly across Slope and Bowman Counties into Adams County. The best exposures and thickest sections of the Ludlow Formation are in the Marmarth area, where it consists of 250 feet of alternating shale, sandstone and lignite beds. The Ludlow thins to the east and interfingers with the Cannonball Formation. The character of the Ludlow Formation in North Dakota is much like that of the Hell Creek Formation which it conformably overlies. This accounts for the difficulty in tracing both the upper and lower boundaries on a lithologic basis. According to C. I. Frye (personal communication, 1965), the upper boundary may be traced by means of a thick, cross-bedded sandstone in the base of the Tongue River Formation over much of the western outcrop area. He also considers the base of the Ludlow Formation to be at the "lowest persistent lignite".

Hares (1928, p. 25-26; 47) has placed the aggregate thickness of the lignite beds at about 30 feet in the Ludlow Formation. He has also stated (p. 46) that these lignite beds generally contain more impurities, such as, marcasite, gypsum and shale than do those of the Tongue River Formation. These lignites are typically darker in color, more jointed, and contain less woody material than Tongue River lignites. One of the lignites, the T-Cross bed, has burned out over large areas in Slope and Bowman Counties to form a thick and striking "scoria" in a number of buttes in the Marmarth area.

Tongue River Formation

The Tongue River Formation was named as a member of the Fort Union Formation by J. A. Taff in 1909 for a series of lignite-bearing strata exposed along the Tongue River in the Sheridan Coal Field, Wyoming. In 1924, W. T. Thom and C. E. Dobbin traced the Tongue River Member into North Dakota on the basis of lithologic similarity with Taff's type section. Erling Dorf elevated the member to formational status in 1940. Seager and co-workers (1942) reclassified the Tongue River as a member, a classification which is still accepted by the United States Geological Survey. The North Dakota Geological Survey considers the Tongue River to be a formation in North Dakota.

The Tongue River Formation consists of terrestrial sands, sandstones, silt, siltstone, clay, shale and lignite. It is characteristically light in color, contrasting in this respect to the dusky, bluish-gray color of the underlying Ludlow Formation and the "somber" beds of the Sentinel Butte Member. At a distance, the Tongue River Formation is characterized by alternating light gray and light tan or buff beds which are occasionally interrupted by pastel beds of "scoria", and dark gray or black lignite seams. The gray beds often have a "salt and pepper" appearance at closer distances. The tan to brown color of other beds is caused by small amounts of disseminated limonitic material.

Variation is perhaps the most typical characteristic of the Tongue River sediments. Within very short distances, both vertically and horizontally, the character of the sediments may change drastically. Despite this, a general repetitive nature of deposition can be discerned. Broadly, the sequence from bottom to top is: a thin gray underclay, which often weathers brown; lignite of variable grade; a clayey siltstone which becomes progressively less clayey, and grades upward into; a cross-bedded, fine sandstone, which in turn grades into; siltstone, and again; another underclay. Many exceptions to this sequence may be observed, however. Local induration by baking, cementation by the action of circulating waters, and the occurrence of channel sands or sandstones often interrupt this sequence.

Localized cementation by carbonate, silica, and limonite in the sands often produces, upon weathering, protruding sandstone ledges, and unusual "log"-like sandstone concretions. Smaller concretions are common in many beds. These commonly have an outer layer of limonitic-stained sand and an inner light gray center.

There are at least six major lignites and a number of minor lignite and lignitic shale beds in the Tongue River Formation (Fig. 7). Some of these beds are very persistent and have a maximum thickness of approximately 44 feet (Roe, 1950, p. 439). Much of the lignite contains considerable woody material. The color of the lignite is brown to dull black, but even the brown weathers to black. Impurities in the lignite include shale, marcasite, gypsum, and small amounts of jarosite.

"Scoria" is a prominent feature in much of the Tongue River strata. The base of the "scoria" is often marked by a variably colored ash bed or a coke-like, protruding ledge. Some of the "scorias" are very thick, locally as thick as 45 feet or more. The HT Butte "Scoria" horizon appears at the base of the Sentinel Butte Member over much of the area of investigation.

Silicified wood occurs at several horizons within the formation. Petrified stumps, which occasionally retain woody centers, occur abundantly.

The thickness of the formation is at least 800 feet in the Sentinel Butte area (Leonard and Smith, 1909, p. 21) and according to Brown (1948, p. 1270), may possibly be somewhat greater near Dickinson, North Dakota. Recent work by C. F. Royse (personal communication, 1965), however, suggests that the maximum total exposed thickness of the Tongue River Formation, including the Sentinel Butte Member is approximately 700 feet. More detailed lithology of the Tongue River Formation will follow in later chapters.

Sentinel Butte Member of the Tongue River Formation.—The upper unit of the Fort Union Group was named by Leonard and Smith in 1907 for the lignite-bearing strata occurring in Sentinel Butte, near Sentinel Butte, North Dakota. The contact of the Sentinel Butte Member with the lower, unnamed member of the Tongue River Formation is essentially a gradational color boundary with minor lithologic change. The Sentinel Butte Member is generally darker and more "somber" in color, usually dark to light gray, in contrast to the buff, light tan and light gray colors of the lower, unnamed member.

The Sentinel Butte Member typically contains more sand, sandstone, and bentonitic clay and less lignite and "scoria" than do the Tongue River beds. The bentonitic clay beds are closely associated with the lignite seams. Much of this bentonitic clay, after wetting and subsequent drying, takes on a "curdy" appearance which is very distinctive. Silicified logs, usually found in the bentonitic layers, are reported by Moldahl (1956) to be more abundant here than in the Tongue River Formation.

The base of the Sentinel Butte Member is marked by the occurrence of the HT Butte Lignite or "scoria" over much of the area. The lignite bed which is referred to as the HT Butte by Hares (1928) has also been known as the F Bed (Leonard and Smith, 1907), R Bed (Leonard, 1925), and as the L Bed (Fisher, 1953). In keeping with the accepted practice of naming stratigraphic units for local geographic place names, and to avoid confusion resulting from various initials applied to this lignite, the name HT Butte Lignite will be used in this paper. The name HT Butte "Scoria" will be used for the "scoria" layer resulting from the burning of the HT Butte Lignite. In the Medora area, this lignite has burned out almost completely to form a persistent, and locally, very thick, "scoria" marker bed. The HT Butte bed, according to C. F. Royse (personal communication, 1965), can be traced for 70 miles north and south, and 30 miles east and west, as either a lignite or "scoria". Leonard and Smith (1909, p. 21) stated that this member has a thickness of 450 to 500 feet at Sentinel Butte, and about 350 feet is present in Bullion and Black Butte.

CAUSES OF BURNING

General

Historically, writers on the burning of coal beds have ascribed ignition to lightning, prairie or forest fires, human activity, spontaneous combustion, or to a combination of these agencies. Undoubtedly, all of these factors have been effective at one time or another in one place or another. Validated cases exist of ignition by lightning, prairie fires, human activity, and spontaneous combustion (Allen, 1874; Rogers, 1918; Griffith and others, 1960). Evidence exists, to be pursued in a later chapter, which indicates that at least some burning took place before man was present in North America. Extensive ignition by prairie or forest fire seems unlikely in many areas of the lightly grassed and lightly forested badlands. Even if heavier vegetative cover in the past were conceded, many persistent lignites have burned in the sides of bluffs and buttes which would not have been approachable by surface fires. As Rogers (1918, p. 1) has concluded, lightning has undoubtedly started some fires, especially in higher hills, but appears to be inadequate to account for the burning of beds over great areas. Further, if burning of the more persistent lignites was often penecontemporaneous with dissection and exposure, as the writer believes, the need for continuous re-ignition would arise as a result of the greater rate of lateral burning compared to the rate of headward erosion. It has also been observed that fires in some of these persistent lignites have burned out, only to be re-ignited in numerous other places along their periphery. The writer concludes, in agreement with others, that burning of lignite beds, which is characteristic of an area greater than 200,000 square miles (Rogers, 1918, p. 1), requires a widespread mode of origin and one less dependent on special conditions.

Spontaneous Combustion

Spontaneous combustion appears to be the one agency which could account for widespread ignition in the western lignite-bearing areas. The occurrence of spontaneous combustion of coals was recognized almost as soon as this fuel came into widespread industrial use. As early as 1805, Lewis and Clark (Reid, 1948; DeVoto, 1953) suggested the possibility of spontaneous combustion in connection with the burning of these lignites, and in 1843, Nicollet stated (1843b, p. 40) concerning the fires:

> They are evidently due to the decomposition, by the percolation of atmospheric waters to them, of beds of pyrites, which, reacting on the combustible materials, such as lignites and other substances of a vegetable nature in their vicinity, give rise to spontaneous combustion. . . .

Since about 1860, this phenomenon has been studied intensively by shipping, mining, underwriting, and industrial agencies. Despite this long history of investigation, there is considerable disagreement as to detail, but the main determining factors have been well outlined. Parr and Kressmann (1910, p. 55-87) have presented an historical review of the summary of opinions of prominent investigators in the field of spontaneous combustion to which the reader is referred for more specific references.

Oxidation begins at ambient temperature with the exposure of lignite. A number of oxidation processes are involved, some of which are relatively slow and release moderate amounts of heat, others of which are rapid and vigorous in action. For every coal, a temperature exists below which oxidation is not ultimately destructive. Above this critical point, oxidation is ultimately destructive and characterized by autogenous reactions. This critical point of autogenous oxidation varies with different fuels, and according to experiments by E. A. Sandreal (written communication, 1962), this temperature may be as low as 70°C for finely divided lignite from North Dakota. It is the processes and reactions which lead up to this temperature then, that are of importance in explaining the spontaneous combustion of lignite.

Both chemical and physical factors enter into spontaneous combustion and the process may be thought of as taking place in several stages. The initial factor in spontaneous combustion is often an external source of heat. In the case of lignite in, or near, the outcrop, this factor is supplied by the direct heat of the sun. Experience in the field has indicated that temperatures on an extremely hot afternoon might reach 55°C, a temperature that has been suggested by Rogers (1918, p. 3) as contributing to spontaneous combustion of lignite. The effect of this external source of heat, is first, to raise the temperature of the mass, thereby accelerating later reactions, and secondly, to accelerate the occlusion of combustible volatiles. In connection with the second point, it has long been recognized that highly volatile coals, such as lignite, are far more susceptible to spontaneous combustion than are less volatile coals. Some writers think that the occlusion of combustible gases and unsaturated hydrocarbons in this range of temperature may be all that is necessary to provide temperatures which would approach the point of autogeny. Other authors place primary significance on the marked avidity of unsaturated hydrocarbons, principally humic acid, for oxygen at low temperatures as the producer of the increment of heat leading to autogeny.

Another physical factor which is conceded by all investigators to be of great importance is the fineness of lignite division. As far back as 1868, Richter (Parr and Kressmann, 1910, p. 84) recognized that finely divided coal was a far more active absorber of oxygen and far more liable to spontaneous combustion than coarser coals. This, of course, is a result of the far greater surface area which is exposed in the finely divided state. Nelson, Snow, and Keyes (1933, p. 1356) state that the rate of oxidation varies inversely as the particle size. This factor becomes particularily important both in the low temperature oxidation of pyrite and of unsaturated hydrocarbons. The fineness of division and the absorbtion of oxygen by unsaturated hydrocarbons has been considered to be an index of liability to spontaneous combustion by some authors.

The presence of sulfur in the form of iron sulfide is a positive source of heat because of the reaction between sulfur and oxygen. Some authors have considered this process to be insignificant, recording instances of spontaneous combustion in coals of low pyrite content. Other writers consider the contribution of pyrite to be merely mechanical, i. e., swelling on oxidation to ferrous sulfate which causes splitting of coals causing increased surface area to be exposed to air. The phenomenon of spontaneous combustion in coals of "low" pyrite content cannot be denied, and the second factor, fineness of division by pyrite oxidation is always important, but it is unreasonable to discount the known increment of heat supplied by the iron disulfide reaction. The careful experiments by Parr and Kressmann (1910), studies by Nelson, Snow, and Keyes (1933), Kabot (1957), and investigations by the writer (1960) have provided convincing data on the importance of this reaction. Experiments by Kabot (1958) indicate that pyrite begins to oxidize to sulfur dioxide gas at 50°C. Thus, it can be seen that the temperature of initiation of the pyrite reaction lies within the range of temperatures that might be reached on a hot day (55°C). There are a number of different interpretations of the reaction between iron disulfide and air. The difference in interpretation is due to the significance placed on the concentrations of reactants. Some of these equations, with thermochemical calculations by the writer, follow:

(1) $2FeS_2 + 7\ O_2 + 2H_2O \rightleftharpoons 2FeSO_4 + 2H_2SO_4$ -324.28 kcal/mol

This is perhaps the most common representation. Equation (1) is a heterogeneous reaction which may be written:

(2) $FeS_2 + 3\ O_2 \rightleftharpoons FeSO_4 + SO_2$ -248.94 kcal/mol

(3) $2SO_2 + O_2 + 2H_2O \rightleftharpoons 2H_2SO_4$ -75.34 kcal/mol

Nelson, Snow, and Keyes (1933), consider the preceding two reactions incomplete without the addition of the reaction:

(4) $4FeSO_4 + 2H_2SO_4 + O_2 \rightleftharpoons 2Fe_2(SO_4)_3 + 2H_2O$ -32.35 kcal/mol

Allen (1910) and Harry Rootman (personal communication, 1959) have suggested the reaction:

$$(5) \quad 2FeS_2 + 11\,O \rightleftharpoons Fe_2O_3 + 4SO_2 \quad -397.65 \text{ kcal/mol}$$

While realizing the complexity of the pyrite oxidation reaction, Lovering (1948, p. 9), assumed that ultimately all iron combined as sulfide changes to ferric hydroxide and represented the reaction:

$$(6) \quad 2FeS_2 + 15\,O + (n+7)H_2O \rightleftharpoons 2Fe(OH)_3 + 2H_2SO_4 + nH_2O \quad -341.18 \text{ kcal/mol}$$

Wilkie (written communication, 1959) and other writers have considered the oxidation of iron disulfide to be mainly due to the activity of certain autotrophic bacteria, and represent the reaction:

$$(7) \quad 4FeS_2 + 15\,O_2 + 2H_2O \rightleftharpoons 2Fe_2(SO_4)_3 + 2H_2SO_4 - {}^{*}\text{I. D.}$$

*Insufficient Data

Regardless of the reaction or reactions chosen to fit the circumstances, it can be seen that all reactions are exothermic and contribute a considerable increment of heat. More important than the absolute amount of heat, however, is the rate at which it is produced, i. e., the rate of reaction. The rate of reaction is influenced by the particle size, catalysts present, and concentration of reactants. All of the reactions are dependent on either two or three reactants and are respectively, second or third order reactions. If one or more of the reactants are in excess, however, the reaction may be reduced in order, and increased in rate. It is probable that both water and air are supplied in excess at the outcrop, resulting in a first order reaction where the lignite is exposed. The action of catalytic agents has recently been realized to be a contributing factor to the rate of reaction. Wilson (written communication, 1950) and Nelson, Snow, and Keyes (1933) have found that organic peroxides, ferric sulfate, and the metabolism of sulfur oxidizing bacteria all catalize the iron disulfide oxidation reaction, and may initiate the exothermic reaction at temperatures as low as 50°C. It is also significant that marcasite, the form of iron disulfide most often present in lignite, undergoes oxidation at a much more rapid rate than does pyrite.

Parr and Kressmann (1910, p. 23-51) have determined that the oxidation of one-fifth of the pyrite in a bituminous coal containing six per cent pyrite would raise the temperature of the mass approximately 70°C, assuming no loss to radiation. They further found that only about one-fifth of the pyrite would oxidize, regardless of the pyrite content. An examination of their calculations (p. 34) shows that this increase in temperature would be even greater for lignite, as a result of the lesser specific heat of lignite. The recalculation of sulfur to equivalent iron dioxide, from data in Mares (1928, p. 54-55), and Brant (1953, p. 5), indicates that iron dioxide content ranges from one to six per cent, and averages about three per cent, in North Dakota lignites. This amount of iron disulfide, particularily where concentrated, should result in raising the mass temperature to temperatures approaching autogeny. Undoubtedly, this additional heat would initiate other reactions, such as the oxidation of unsaturated hydrocarbons, which would lead to initiation of self-sustaining reactions. Many investigators consider the content of more than two per cent iron dioxide to be potentially dangerous with respect to spontaneous combustion.

As indicated by the experiments of Parr and Kressmann (1910, p. 52), the tendency towards oxidation in any coal will be facilitated by moisture. The factor is particularily important in the pyrite reaction, and may also be very important in forming ozone, which according to many authors may initiate and catalyze the low temperature oxidation of unsaturated hydrocarbons. In studies on coal containing from 12 to 15 per cent moisture, Parr and Kressmann (p. 52) found: "Without exception, . . . the wetting of the coal increased the activity as shown by the ultimate temperature". North Dakota lignites typically contain from 30 to 45 per cent moisture. It is also significant that some of these lignites are good aquifers, because water from overlying, permeable beds is often trapped in the fractured lignite by underlying, impermeable clay beds.

A later stage of spontaneous combustion occurs when temperatures are raised to the vicinity of 120°C. At this temperature hydrocarbon compounds oxidize with the formation of CO_2 and H_2O. This reaction is particularily important as the higher quantity of heat supplied by the oxidation of carbon and hydrogen may quickly raise the temperature of the mass to the point of autogenous action.

The last stage of spontaneous combustion begins with the autogenous or self-sustaining reaction, and ends with ignition, which may occur at a temperature as low as 70°C, if lignite is very finely divided. The autogenous reaction may begin at temperatures from 70 to 200°C. When the reactions become autogenetic they are no longer dependent on other sources of heat to maintain the reacting temperature. At these temperatures the decomposition of lignite begins, which further increases the temperature.

From the preceding discussion of chemical reactions, the writer would suggest the following minimum series of reactions to account for spontaneous combustion of lignite:

(8) $4FeS_2 + 11\ O_2 \rightleftharpoons 2Fe_2O_3 + 8SO_2$ -197.65 kcal/mol

(9) $FeS_2 + 3\ O_2 \rightleftharpoons FeSO_4 + SO_2$ -248.94 kcal/mol

Low Temperature

(10) $2SO_2 + O_2 + 2H_2O \rightleftharpoons 2H_2SO_4$ -75.34 kcal/mol

(11) $C + O_2 \rightleftharpoons CO_2$ -94.05 kcal/mol

(12) $FeS_2 + O_2 \rightleftharpoons FeS + SO_2$ -51.16 kcal/mol

Higher Temperature

(13) $FeS + H_2SO_4 \rightleftharpoons FeSO_4 + H_2S$ +14.31 kcal/mol

(14) $2H_2S + SO_2 \rightleftharpoons 3S + 2H_2O$ -16.64 kcal/mol

This series is not suggested as a complete representation of reactions leading to spontaneous combustion but only accounts for products which are known to form in the process. The reaction which had the largest negative free energy was chosen whenever two reactions were proposed for the same products.

Although the extent to which carbon enters the series is unknown, the total liberation of heat calculated from the series suggested (8 through 14) is approximately 100 Btu per pound of lignite, containing three per cent pyrite.

The liberation of heat and the rate of reaction are not the only factors of importance leading to spontaneous combustion, however. Even if both of these factors are of considerable magnitude, the heat may not be retained if the thermal conductance of the surrounding media is high. According to data in the Handbook of Physical Constants (1942, p. 263), the thermal conductance of lignite is very low, and even that of the surrounding material, mainly clay and silt, is relatively low. It would therefore be expected that the heat loss by transfer through the mass would be slight.

Rogers (1918, p.3) has stressed the probability of spontaneous combustion in piles of lignite which accumulate at the base of a lignite seam when it is undercut by a stream. He believes that the low temperature oxidation processes, and the conservation of heat within the pile would lead directly to spontaneous combustion. It appears to the writer that these conditions are, perhaps, more specialized than necessary. In the field, the writer found accumulation below a seam to be relatively rare and the occurrence of burning lignite seams in place to be far more common. The writer therefore believes that many fires ignite directly in the lignite seam, and that the pressure of the overlying overburden may be a factor in spontaneous combustion. Both the pressure from overlying material, and the insulative value, should be greater when the lignite is in place.

Several generalizations can be made about the burning of lignite in outcrop. First, the major cause of burning had to be a recurring phenomenon. Secondly, those lignites which have a high content of iron disulfide and moisture, and are in a finely divided state, are more liable to spontaneous combustion. Third, beds of impure coal burn less commonly than those of cleaner or less shaly coal. Finally, thin beds are less commonly burned than thick ones.

Lignite and Ash Analysis

The Fort Union Group is estimated by Roe (1950, p. 435) to contain 100 beds of lignite over four feet thick. According to the same writer, the greatest number, and thickest beds, are contained in the lower 700 feet of the Tongue River Formation. The samples of lignite for which analyses are given in Table 1 were, with one exception (Harmon Lignite), taken near the upper boundary of the lower, unnamed member of the Tongue River Formation.

Most of the North Dakota lignite can be classified as brown lignite, as can most of the lignites examined in the area of investigation. These brown lignites, however, are of higher grade than the black lignites, which are typical of the Ludlow Formation. Upon weathering, the lignites tend to become blacker in color, and the low ash content lignites take on a glossy, bright black appearance (Roe, 1950, p. 438). This appearance is typified by sample No. 20,573, collected by the writer from an exposure at location 101 (Fig. 4) in the HT Butte Lignite. This sample shows the low ash content (Table 1) which is typical of this type of weathering (Roe, 1950, p. 437). The high Btu value (Table 1) for this lignite is also significant. The composition of this same lignite is apparently quite variable, however, as other samples (No. 20,888 and No. 20,889) taken at, and near, location 17, weather to a dull black color and have a relatively high ash content. These two samples are particularily "fat" lignites, having a volatile content considerably in excess of the fixed carbon content. The higher ash content is probably due to the greater number of shaly layers present. The Btu values of these two lignites are approximately 2,000 units less than the same lignite at location 101. Woody material does not appear to be common in the HT Butte Lignite, but this may also reflect the very limited exposure of this bed. Other beds, lower in the section, contain much woody material, and occasional stumps and

Table 1.--Proximate analysis of lignite and ash

Location	Sample Type	Lab. No.[a]	% Moisture	% Ash	% Volatile Matter	% Fixed Carbon	% Combustible	Btu
Loc. 17, (Fig. 3)	HT Butte semi-coke	20,572	7.5	---[b]	47.7	---	---	1,794
Loc. 101, (Fig. 4) Sully Creek	HT Butte Lignite	20,573	10.4	4.8	43.0	41.8	---	9,612
sec. 23, T. 140 N., R. 101 W.	HT Butte Lignite	20,574	13.2	10.6	41.4	34.8	---	7,353
Loc. 17, (Fig. 3)	HT Butte Lignite	20,888	10.0	14.7	45.7	29.6	---	7,269
Loc. 21, (Fig. 3)	HT Butte Lignite	20,889	8.6	14.4	40.7	36.3	---	7,857
sec. 15, T. 132 N., R. 102 W.	Harmon Lignite	(Brant, 1953, p. 5)	44.5	5.2	24.8	25.5	---	6,062
Loc. 7, (Fig. 3)	Var. ash	20,890	6.5	85.9	7.6	00.0	7.6	-----
Loc. 25, (Fig. 3)	Wh. ash	20,891	7.8	86.8	5.4	00.0	5.4	-----
Loc. 19, (Fig. 3)	Wh. ash	20,892	6.1	84.2	8.7	1.0	9.7	-----
Loc. 41, (Fig. 3)	Var. ash	20,893	0.6	76.4	23.0	00.0	23.0	-----

[a] North Dakota School of Mines Laboratory Number

[b] 49.9% at 750°C; 45.2% at 1000°C

branches. Compared to other lignites in the area, the lignites of the Tongue River Formation are quite clean if the shale partings are discounted. According to Roe (1950, p. 438), calcite and siderite are rare, and sulfur content is relatively low. The writer would agree with Hares (1928, p. 46), however, that iron disulfide and gypsum are locally abundant. Roe (p. 437) has stated that the low ash lignites (less than 5 per cent) have a particularily high lime and magnesia content. In the higher ash lignites, the ash contains more alkalies, silica, and alumina, but is still more basic than ash characteristic of older coals.

The beds of lignite vary in thickness from mere streaks to over forty feet, without a parting. Lignite horizons are quite continuous, but individual beds may thin and almost pinch out before they thicken again. According to C. F. Royse (personal communication, 1965) the HT Butte Lignite or "scoria" can be traced intermittently over an area of 2000 square miles, and for more than 70 miles in one direction, in southwestern North Dakota.

Roe (1950, p. 439) has suggested that plant material accumulated in swamps that were usually connected during times of swamp conditions. Different rates of accumulation and subsidence within the individual swamp basins account for the irregular depth of accumulation of plant materials, and subsequent variation in thickness of lignite. Apparently, in the case of the persistent lignites, accumulation was essentially isochronous, with definite lapses in swamp conditions accounting for the recurring deposition of sediments between.

A number of products are formed directly from the burning of lignite. The most common of these is ash which occurs in outcrop in various forms. Perhaps the most striking is the thick white or light gray colored ash which is particularly well developed in the buttes of the Marmarth area (Plate II, Fig. 6). This ash forms from the burning of several different lignites, but is typically thick and prominent in beds formed by the burning of the T-Cross Lignite. In Pretty Butte, this white ash approaches four feet in thickness. White ash is typical of particularly clean-burning lignites which have apparently burned under optimum combustion conditions. Usually, however, these ashes become darker into the subsurface, and the white color at the surface may be in part due to capillarity drawing soluble sulfates to the surface of the outcrop.

Another striking ash is the dark-colored, compact, thick, vesicular "semi-coke" (or "coke" of some reports), which forms resistant protruding ledges below some thick "scoria". This "semi-coke" is locally formed by the HT Butte, Harmon, and T-Cross Lignites, and is typically associated with thick, strongly metamorphosed "scoria". It is believed that this "semi-coke" is formed under strongly reducing and distilling conditions. This material is characterized by a high fixed carbon to volatile ratio. Thickness of "semi-coke" ranges up to three feet. The proximate analysis of this material (No. 20,572) did not, however, yield the expected results. According to Miss Adalynn Rasmussen (personal communication, 1964) this may be the result of analyzing the "semi-coke" as a true coal. It is probable that the remainder of the material which was reported as ash may really be a poorly combustible form of fixed carbon, and that the volatile matter has resulted, in part, from the decomposition of a sulfate material at higher temperatures.

The terms, clinker and cinder have also been used to describe material similar to "semi-coke". "Clinker" is here defined as massive, dark, coherent ash resulting from the burning of lignite which had a high content of impurities. The formation of "clinker" is favored by the presence of partially petrified wood, marcasite, and gypsum. "Clinker" is similar in appearance and formation to the furnace product.

Between these two extremes lie less cohesive ashes of various, and variegated colors. Most of these ashes show some variegation, but black, purple, and reddish ashes are fairly common. The variegated ashes commonly show streaks of white, purple, red, lavender, and black. This varigation is probably caused by burning of lignites of variable composition within a single seam. It is also possible that these variegated ashes reflect varying conditions of oxidation and reduction in the course of burning. Some of the lignitic shales apparently burn to reddish and purplish ashes. Analyses Nos. 20,890 to 20,893 (Table 1) were carried out on ashes of the variegated type from the burning of the HT Butte Lignite in the South Unit of Theodore Roosevelt National Memorial Park. All four ashes contain very little, if any, fixed carbon, which would indicate rather complete burning.

X-ray diffractograms indicate that the ashes typically contain gypsum, calcite, quartz, dolomite, and anhydrite, in approximately that order of magnitude. The anhydrite is derived from gypsum in the lignite. Chemical tests also indicate the existence of sulfates. Numerous reports indicate that sodium is present in amounts up to 10 per cent which may be combined with the sulfate. Under the binocular microscope, small amounts of hematitic material, and perhaps, marcasite, can be seen. It is also likely that some iron sulfates are present.

It should be mentioned that all analyses were made on air-dried material which has lost considerable moisture since collection at the outcrop. The lignites can be best compared to other lignites on a moisture free basis. These data do, however, indicate that the characteristics of these "scoria"-forming lignites are about average for North Dakota lignites, and show no unusual properties. The sample of lignite taken from the HT bed at Sully Creek (No. 20,573) has a rather high Btu value, but this same lignite in nearby areas has a Btu value which is considerably lower.

CHARACTER AND COMPOSITION OF SOME PARENT SEDIMENTS

General

The sediments which are discussed in detail are contained in the lower part of the Sentinel Butte Member and the upper part of the unnamed member of the Tongue River Formation. It should be made clear that although the material of the Tongue River Formation is often referred to as sediment, this is not entirely true. A small, but significant quantity of the former sediment has been cemented or otherwise lithified to a sedimentary rock. Therefore, the Tongue River Formation is composed of both sediments and sedimentary rocks.

The area which received the Tongue River sediments was apparently a vast low-lying and intermittently subsiding floodplain over which meandering and braided streams flowed through poorly drained inland swamps, ponds, and lakes. The evidence for these low-gradient, low-velocity streams lies in the general fine character of the sediments, their angularity, the evidence from channel sands of frequently shifting streams, and the widespread occurrence of lignite. During periods of slight clastic deposition, swamp conditions lead to the irregular accumulation of vegetative material in differentially subsiding, but connected swamp basins. Crossbedding of sandstones, channeling, overlap, and interfingering suggest intermittent diversion and change of the sediment-bearing streams that buried the subsiding, incipient lignite bais. With the exception of lignite, and some volcanic grains, all these sediments are fluviatile in origin. Terrestrial mammal, invertebrate, and plant fossils attest to the non-marine origin of these sediments. The paludal lignites are often underlain by a bluish, brown-weathering underclay which probably represents the ancient soil or substrate upon which the swamp plants grew. According to Brown (1962, p. 12) the abundant plant remains in the sandstones, clays, and shales show that vegetation was more or less luxuriant on the higher parts of the flood plains.

An often recurring sequence of sediments (p. 35) indicates the probability of cyclic deposition in the Tongue River Formation in this area. While exceptions to this sequence are frequent, the writer has found cyclic deposition to be characteristic of the Tongue River sediments in the area of intensive study. Gerhard (1963) has also discovered cyclic deposition in the lower Fort Union sequence in eastern Montana.

Tisdale (1944, p. 31) has stated that the heavy minerals in the Tongue River beds indicate that the sediments were probably derived from a metamorphic complex such as the Black Hills or as may have existed in western Montana. The writer would concur that heavy minerals studied in the present investigation would indicate a metamorphic source, and that the angularity of some of the less resistant minerals, such as feldspar, would indicate relatively short transport and a general lack of chemical weathering. It is probable, however, that most of the angular feldspar is indicative of a volcanic source, and aeolian transport, from a location far to the west.

Grain Size Distribution

It is obvious from the preceding discussions, or to one familar with the Tongue River Formation, that a few analyses of the sediments will not suffice to characterize the unit. Therefore, the data presented should be considered indicative of the character of sediments examined in a very limited area. It is even questionable whether these analysed sediments are characteristic of sediments which closely surround them. The writer believes, however, on the basis of considerable supplementary field observation, that the trends indicated by these data are characteristic of sediments in the area of intensive study.

A detailed vertical suite of samples was collected from location 17 (Fig. 3). This suite is particularly significant in that it directly overlies the HT Butte Lignite, and is bordered on either side by HT Butte "Scoria", which has formed from similar sediments. Samples were collected at two and one-half foot intervals, from the top of the HT Butte Lignite to the top of the butte (44 feet).

Grab samples from five locations (p. 26) in the "scoria"-bearing area were also collected which are believed by the writer to represent the geographic range and lithologic variation of sediments that were known to have formed "scoria". As good stratigraphic control of these samples was lacking, and as their direct significance could not be evaluated, lithologic characteristics were not investigated as completely as were those from the suite collected at location 17. These grab samples were also used for the firing tests in the following chapter.

In the case of the grab samples, the grain size distribution was determined by standard hydrometer analysis. The values, which were determined for the sand, silt, and clay content only, were later checked by pipette analysis. The values determined by both methods were essentially the same. After wet-sieving, only a few particles of vegetative material were retained on the +2 mm sieve. In fact, only two samples [No. (3), 18%, and No. (5), 6%] contained a significant amount of sand sized grains. Microscopic investigation indicated that these sand grains were dominantly of the very fine sand grain size. The other three grab samples [Nos. (1), (2), and (4)] contained only silt- and clay-sized grains in a rather consistent proportion of 13-20 per cent clay and 80-87 per cent silt (Fig. 5). Even samples No. (3), and No. (5) showed a silt-clay content in this same range. All five of these samples can be classified as silts, or siltstones, depending on the degree of cementation. In these five samples the silt-clay ratio remained relatively constant within a narrow range, and the main variation occurred in the content of sand. These grab samples are indicated on the triangular diagram of grain size distribution (Fig. 5) by circled numbers.

Samples collected from the vertical sequence at location 17 (Fig. 3) were subjected to more detailed analysis. The sand-sized fraction was dry-sieved to yield fractions of +1, +2, +3, and +4 phi grades. The silt and clay content was determined by pipette analysis. Aliquots were drawn to yield +4, +6, +8, and +9 phi grades. Curves were drawn through points calculated from the weighted sediments, and the values of median diameter, first and third quartile diameter, quartile deviation, sorting coefficient, and log of the sorting coefficient to the base 10 were determined in phi notation (Table 2).

The placement of the samples as points on the sand-silt-clay triangular diagram (Fig. 5) shows that the majority of samples are grouped between the limits of 10-25 per cent clay. This range is limited in comparison to the variation in silt (1-95 per cent) and sand (0-76 per cent) content. Several striking exceptions are apparent, however. Sample 1, taken at the contact of the lignite and overlying sediment is a very fine-grained clay which is composed of approximately 60 per cent clay of ~~less~~ finer than +9 phi size. Another exception is sample 18, taken near the top of the section at 42.5 feet. This sample is a very poorly sorted, sandy clay and indicates a major change in deposition. The median diameters of the sand grains tend to increase with increasing distance upward from the lignite to about 38 feet, where there is a tendency towards decrease in diameter for the remainder of the distance to the top of the butte (44 feet). A small reversal occurs at about 10 feet (Table 2). The average mean diameter for the sand grains in all of the samples is approximately 5.5 phi. This indicates that the dominant sediment size in this suite of samples is coarse silt. The quartile deviation generally tended to decrease with distance upward from the lignite to about 35 feet (sample 15), then a reversal in trend towards increased deviation occurred (Table 2).

The majority of the coarser sediments are very well to well-sorted sediments (Krumbein and Pettijohn, 1938, p. 232). Sample 5 is a "normally" sorted sediment, and sample 7, and probably sample 18, show very poor sorting. Grain size data was insufficient to complete the cumulative curves for samples 1 and 18, but if their curves are extrapolated in the clay region, it would appear that sample 1 is the

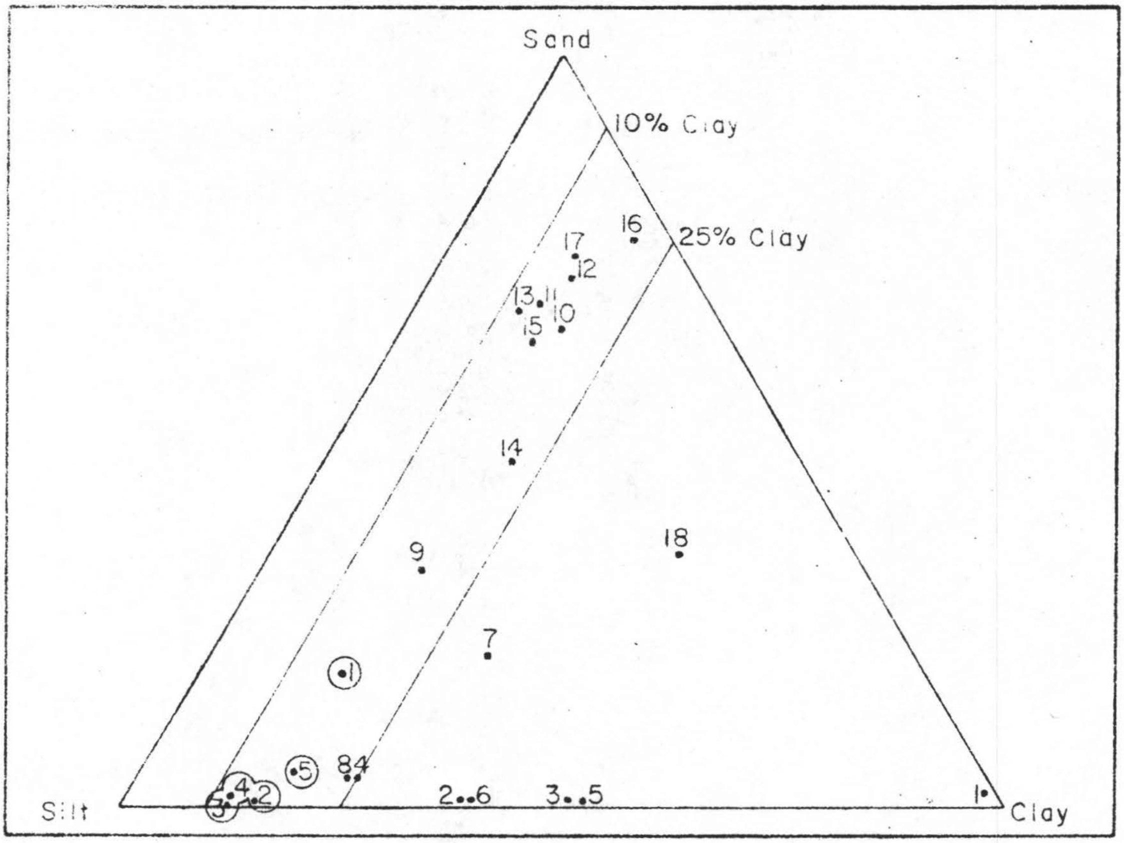


Fig. 5.--Triangular diagram of sand-silt-clay ratios for some parent Tongue River Formation sediments.

Table 2.--Comparison of quartile measures of sediments at location 17

Sample Number	Dist. above HT Butte Lignite	Median ϕ	QDϕ	Q1ϕ	Q3ϕ	So	Log_{10} So
1.	0 feet	9.1	----	8.9	---	----	-----
3.	5	7.8	1.35	6.2	8.9	2.55	0.406
5.	10	8.1	1.60	5.9	9.1	3.00	0.477
7.	15	5.1	2.15	4.3	8.6	4.48	0.651
9.	20	4.8	1.00	4.0	6.0	2.00	0.301
11.	25	3.6	1.00	3.3	6.0	2.00	0.301
13.	30	3.5	0.55	3.3	4.4	1.45	0.161
15.	35	3.7	0.65	3.4	4.7	1.55	0.190
16.	37.5	3.3	0.40	3.1	3.9	1.35	0.130
18.	42.5	5.8	----	---	3.9	----	-----

best sorted sample in the sequence (So = 0.3), and that sample 18 shows the poorest sorting (So = 7.5). The next greatest variation, for which the data is complete, occurred in sample 16 (So = 1.35) and sample 7 (So = 4.48). In comparing the logs of these last two samples (Table 2) it can be seen that sample 16 is about five times as well sorted as sample 7. The variation for samples 1 and 18 would be far greater, as determined by extrapolation of their curves.

These data, and the observations of several field seasons, suggest a number of preliminary conclusions concerning these upper Fort Union sediments. It would appear that the dominant grain size of these sediments generally lies in the silt range. The coarser sediments are composed of a predominant percentage of grains in the fine sand to coarse silt range. Cyclic deposition is recognized in the character of the sediments, both from these data, and from observations in the field. The general trend is toward increasing amounts of relatively coarse grains with distance upward from the lignite. This trend eventually reaches a local climax, and the proportion of coarse grains then progressively decreases to the point that the sediment can be classed as an underclay, which underlies another lignite. Very fine, and well-sorted clays typically overlie the lignite for distances of a few inches up to several feet. These clays and the relatively fine sediments which most closely overlie them would suggest that the dominant type of "scoria" produced by the action of burning lignite would be baked and melted shale or mudstone, a fact which is confirmed by field observation.

Lithology and Mineralogy

The mineralogy of these sediments was studied by subjecting the wet-sieved, sand-sized grains to various combinations of optical, separational, staining, chemical, and X-ray techniques. In the case of the grab samples, additional quantities of coarse silt size material were analyzed. The retained sieve material was dried, then split by the use of a micro-splitter to obtain samples of manageable size. The reduced samples were further divided into "light" and "heavy" fraction by the use of acetylene tetrabromide (2.96 sp gr) in separatory funnels. Permanent mounts of the "light" minerals were made by sprinkling several hundred grains on a petrographic slide covered lightly with warmed Lakeside #70 cement. The slides were then etched with hydrofluoric acid fumes, and stained alternately with sodium cobaltinitrite and Eosine "B" stain to identify quartz, chert, and the general type of feldspar present. A modified point count analysis was carried out under the binocular microscope to determine the respective quantities of these minerals. Mineral counts were obtained by identifying and counting the minerals present under the field of an ocular grid. The slide was moved about on the stage with as little selectivity as possible until a total of 333 grains were recorded on a digital counter. This number of points would result in a reliability of more than 95 per cent at the 95 per cent confidence level if the point count method were strictly adhered to, but inaccuracy in identification, and deviation from the standard point count theory probably result in a deviation of plus or minus 10 per cent from some figures stated in Table 3.

Some of the "heavy" mineral fractions were mounted in Lakeside #70 to be studied as permanent mounts. Some of the "heavy" minerals

Table 3.--Light Mineral Analysis of some Tongue River Formation Sediments

Location	Dist. above HT Butte Lignite	% Quartz	% Na-Ca Feldspar	% K Feldspar	% Carbonate[a] (Dolomite)	% Gypsum	% Carbonaceous Material	% Heavy Minerals
(Loc. 17) 1	0.0 feet	-	-	-	14.6	-	-	-
2	2.5	10	14	1	21.2	37	38	-
3	5.0	15	21	1	8.3	51	6	-
4	7.5	26	21	2	11.8	35	9	-
5	10.0	20	18	1	12.8	43	14	-
6	12.5	29	19	1	13.3	37	5	-
7	15.0	35	31	1	11.4	28	1	-
8	17.5	38	28	1	13.9	26	3	-
9	20.0	45	26	1	14.8	24	2	-
10	22.5	50	26	0	13.4	21	-	-
11	25.5	50	21	1	10.4	26	-	-
12	27.5	47	31	1	12.6	20	-	-
13	30.0	47	30	0	12.8	21	-	-
14	32.5	44	29	1	18.0	21	-	-
15	35.0	50	31	1	10.0	13	-	-
16	37.5	48	30	1	8.6	15	-	-
17	40.0	40	32	1	13.0	21	-	-
18	42.5	44	31	1	6.8	20	-	-
NW Park (1)	-	-	-	-	15.7	-	-	-
Buck Hill (2)	-	-	-	-	25.0	-	-	-
South Heart (3)	-	-	-	-	19.1	-	-	-
Hebron (4)	-	-	-	-	10.2	-	-	-
Top of HT (5)	-	-	-	-	6.0	-	-	-
99bs	-	-	-	-	2.7	-	-	-
HTs	-	-	-	-	2.7	-	-	-

[a]Carbonate calculated seperately.

were also investigated by immersion liquids. Isolated mounts of individual "heavy" minerals were made to assist in the determination and estimation of heavy mineral content in the permanent slides. In the case of both "light" and "heavy" minerals, further investigation was carried out by isolation of the minerals of interest, and study under the petrographic microscope.

A number of the samples were also analysed quantitatively in powder packs by X-ray diffraction. Lacquer slides of some "heavy" mineral separations were also investigated.

Carbonate content for all samples was determined by volumetric analysis, and calculated as dolomite (Herron, Hicks, and Robertson, 1959, p. 139-144).

Clay minerals were obtained during the pipette analysis at the +9 phi limit. Sedimented slides were prepared from this aliquot, and qualitatively analysed by X-ray diffraction. Other sedimented slides of the same material were analysed for specific clay minerals by staining techniques (Grim, 1953, p. 274).

Sand and Sandstone

Beds of sand or poorly cemented sandstone compose about 30 per cent of the lower part of the Sentinel Butte Member and the upper part of the unnamed member of the Tongue River Formation in the area of study. The beds range in thickness from a few inches to approximately 50 feet. A particularily persistent ledge of well cemented sandstone is located from 10 to 30 feet below the HT Butte Lignite. This ledge is typically two to six feet thick, and it frequently erodes to a lens-, log-, or pod-like shape. The cement in this sandstone ledge is a carbonate, but limonitic cements are common in other sandstones, and silica cement occurs occasionally. Individual beds typically vary greatly in thickness and may pinch out rapidly within a few hundred feet.

The color of the sand and sandstone beds ranges from a light gray to a dark buff color. Most of the sand, and sandstone beds which are cemented by carbonate or silica cement, are light gray to light tan in color. These beds also contain more minerals apparently supplied from a volcanic source. Disseminated limonitic particles contribute the darker colors to some sandy beds, and limonitic-cemented sandstones may be almost brown in color. Cross-bedding is particularly prominent in the limonitic-cemented sandstones.

The "light" mineral suite of the sand and sandstone beds is relatively simple. The predominant minerals are quartz, plagioclase, dolomite, and gypsum. Quartz is the most common mineral, composing from 10 to 50 per cent of the sandstone. The quartz content generally increases with distance upward away from the lignite (Table 3). The quartz grains are angular and clear. Chert is present in amounts of five per cent or less.

Plagioclase is surprisingly abundant and is usually the second most common constitent. At least two distinct species are present. Oligoclase is by far the most common feldspar. It ranges in amount from 14 to 32 per cent, increasing in content with distance upward from the lignite. The second species of plagioclase is a sodic andesine, which may compose as much as five per cent of the sediment. Orthoclase is also present, but in amounts of two per cent or less. The different species of feldspar were indicated by optical microscopy, proved by use of immersion liquids, and confirmed by X-ray diffraction.

Gypsum, probably in the form of selenite altering to anhydrite, may locally be the most abundant mineral in sediments near the lignite. The gypsum ranges from 51 to 13 per cent, decreasing in amount with distance upward (Table 3). While the optical characteristics appeared to be distinct for gypsum, the X-ray diffractograms did not show the presence of this mineral. It is suspected that the gypsum may be altering to anhydrite, and that the X-ray "peaks" lie somewhere between those characteristic for gypsum and anhydrite. Staining tests confirm the presence of both of these minerals.

The carbonate mineral is mainly dolomite, although small amounts of calcite and siderite are present. In the vertical suite (Loc. 17), dolomite ranges in content from 6.8 to 21.2 per cent. Grab sample No. (2) from the Buck Hill area contained 25.0 per cent (Table 3).

Most of the samples also contained small amounts of sericite. There is clearly a transitory relationship between some of the clay minerals in the silt particles, and sericite. Some of the feldspars may also be sericitized. Other minerals which are present in some samples are biotite, microcline, magnetite, and an iron silicate which was detected in X-ray diffractograms.

The freshness and angularity of most of the grains, and particularly the feldspars, is striking. Most of the grains are angular to subangular. Only the orthoclase seems to be weathered and somewhat turbid. The freshness and angularity of these grains would suggest a volcanic origin, limited or aeolian transport, and a lack of chemical weathering. The largest grains were typically oligoclase and gypsum.

Silt, Mudstone, Clay, and Shale

Tisdale (1941, p. 28), Benson (1952, p. 49), and Meldahl (1956) have estimated that combinations of silt, clay and their lithified equivalents compose more than 50 per cent of the Tongue River Formation. In the area of study, the writer would further estimate that the Tongue River sediments are composed of about 45 per cent silt-sized material and 25 per cent clay-sized material. The beds range in thickness from a few inches to 40 feet in thickness. Their color range is from light blue-gray to dark brown, depending on the amount of carbonaceous and limonitic material present.

Relatively pure clays are rare, and are commonly encountered only directly above and below the lignites. Clay beds which show the "bentonitic" weathering characteristics are very uncommon in this area. Most of the clay beds contain from 10 to 20 per cent carbonate, mainly dolomite, which acts as a cementing agent. These beds bake to a hard surface in the summer sun, but when wetted, regain their original plasticity.

Clay minerals were initially identified by stain analysis, but were only partly confirmed on X-ray diffractograms. The clay mineral, montmorillonite, was found in all samples. It composed from 60 to 80 per cent of all clay minerals in grab samples Nos. (1), (2), (4), and (5), as determined by staining methods. Illite was also found to be present in lesser amounts in all samples. Samples No. (3) and No. (4) contained 50 and 20 per cent nontronite, respectively.

The clay minerals in the vertical suite (Loc. 17) were detected only by X-ray diffraction and no attempt was made to determine amounts. Only montmorillonite, and subordinate amounts of illite were found.

small amounts of sericite were also detected in these samples.

Carbonaceous material is common in the silts and clays, especially near the lignites. In the vertical suite, the carbonaceous material decreases from 30 per cent near the lignite, to an insignificant amount, at about 15 feet above the lignite.

Heavy Minerals

Heavy minerals were separated by the use of acetylene tetrabromide (2.96 sp gr). Only those samples which contained appreciable amounts of sand (samples 9 through 18, Loc. 17) were studied. Only one of the samples contained more than five per cent heavy minerals (sample 11, 5.3 per cent). All of the other samples contained less than one per cent, ranging from 0.8 per cent in samples 14 and 15, to 0.2 per cent in samples 10 and 17 (Table 4).

An aggregate of limonitic material with an iron sulfide core was by far the most common heavy "mineral" encountered. These relatively large particles (+3 phi) appear to be altering from marcasite grains. Apparently, weathering of marcasite grains released iron oxides which cement surrounding clay minerals into limonitic concretions. This material makes up more than four per cent of the total sediment in sample 11 (Table 4).

Almandite and epidote are the next two most common heavy minerals, and they are present in approximately equal amounts. Almandite ranges in amount from five to 30 per cent, and epidote from a trace to 25 per cent.

The almandite is pink to colorless, and angular in outline. High relief, isotropism, concoidal fracture, and the index of

Table 4.--Heavy Mineral Analysis of some Tongue River Formation Sediments

Loc. 17 Sample No.	% Hv. Min. in Sample	% of Heavy Mineral Fraction															
		Limonitic Material	Biotite	Epidote	Alamandite	Magnetite	Apatite	Zircon	Rutile	Hornblende	Pyroxene	Anhydrite	Siderite	Chlorite	Sphene	Tourmaline	Others
9	0.5	60	5	5	10	5	5	2	T	-	-	5	-	5	-	-	
10	0.2	20	15	20	20	5	5	3	T	-	-	-	-	10	-	T	
11	5.3	90	5	T	T	5	-	-	-	-	-	-	-	-	-	-	
12	0.7	30	15	15	20	5	5	2	T	T	T	-	-	5	-	T	
13	0.2	5	10	20	30	5	10	5	1	-	T	5	-	5	-	-	
14	0.8	70	5	5	5	3	5	2	1	T	T	-	-	1	-	-	
15	0.8	50	5	10	20	5	2	2	T	?	?	-	-	2	-	-	Trace of Muscovite and Kyanite
16	1.0	5	10	25	30	2	10	10	2	T	?	2	2	2	-	-	
17	0.2	15	10	10	10	10	15	10	5	T	-	5	-	T	T	-	Trace of Leucoxene
18	0.8	2	15	20	15	10	10	5	T	T	T	-	-	10	T	-	

refraction serve to identify it. Numerous magnetite inclusions were noted in many grains.

Epidote occurs in subangular grains which are a light olive green in color. Pleochroism from light yellow-green to colorless, high refringence, and high birefringence are characteristic.

Biotite occurred in all samples and ranges in amount from five to 15 per cent. The flakes range in color from reddish brown to black. Traces of muscovite are present in some samples.

Magnetite, apatite, and zircon were also relatively common, ranging in amount from two to 15 per cent. Apatite and zircon were not present in sample 11 (Table 4). Magnetite was separated by hand magnet.

Apatite occurs as subrounded, colorless grains which were identified by low birefringence and the indices of refraction.

Zircon appeared as sharply euhedral, pyramid terminated prisms. The crystals were typically colorless or very light yellow in color. Crystal habit and parallel extinction identified this mineral.

Chlorite appeared in many of the samples in amounts of 10 per cent or less. It was readily identified by its green color and micaceous habit.

Other minerals, which occurred in some of the samples in amounts of five per cent or less, are rutile, anhydrite, hornblende, sphene, several pyroxenes, kyanite, leucoxene, sericite, and blue tourmaline (Table 4).

The writer would agree with Tisdale (1941, p. 31) that this heavy mineral assemblage, and particularly the trace minerals, could indicate a metamorphic source. The occurrence of angular kyanite and tourmaline would be difficult to account for by other than a metamorphic source.

FIRING CHARACTERISTICS OF SOME PARENT SEDIMENTS

Purpose and Preparation

The purpose of this part of the study was to investigate the firing properties of some Tongue River Formation sediments which were similar to those sediments which had been metamorphosed to "scoria" in the southwestern part of North Dakota. To accomplish this, samples of these sediments were fired to form artificial analogs of "scoria". These grab samples were selected to be representative of the range of petrographic composition and geographic location (p. 26) of sediments known to have formed "scoria" in North Dakota. The characteristics of these sediments were discussed in the preceding chapter and the mineralogic data for specific samples may be found in Tables 3 and 4.

The samples were prepared for firing by grinding to a size which would pass through a Tyler No. 4 (4.76 mm) sieve and be retained on a No. 3 (6.73 mm). This material was then preheated to a relatively high temperature (530-650°C) to eliminate "popping" which results from too-rapid expansion of contained water. Small (1 3/4 X 2½ X ½ inch) stainless steel trays were constructed to hold from 25 to 35 pieces of the preheated material.

A Harper Electric Globar furnace was used for the firing tests. The large door opening of the furnace was reduced by blocking with fire brick to reduce heat fluctuation. The temperature was raised from the preheating temperature by 10°C increments. At each 10°C increment a tray of sample was inserted, and the temperature was held constant for five minutes. The trays were then removed and allowed to cool at room temperature. Temperatures were checked to plus or minus 0.5°C by a thermocouple connected to a direct-reading potentiometer.

Color Changes

It is believed by the writer that color changes produced at known temperatures in the samples should be indicative of the temperature ranges which produced the colors in similar sediments metamorphosed under natural conditions.

Little color change took place at temperatures below 810°C. The slight change that did occur, i. e., a slight tendency towards lightening of the original color, is mainly a result of volitalization of carbonaceous material, and possible bleaching from sulfur and carbonate dissociation (Wilson, 1927, p. 155).

In the range between 810-870°C, however, a distinct reddening or darkening occurred in all samples except No. (1) (NW Park, Plate I). This color change indicates the formation of ferric oxides from iron compounds in the sediments. The lack of reddening in sample No. (1) may be a result of low iron content. A chemical analysis for iron in this sediment showed a content of 1.9 per cent.

At temperatures above this range the samples gradually darkened first to a brownish color, and then to a greenish tint at the fusion point. This tendency towards darkening at elevated temperatures appears to reflect ferric oxide dissociation to ferrous oxide.

At the point of complete fusion (1150-1260°C), shades of olive were acquired by all specimens. This coloration results, apparently, from the addition of lime, as a flux, to the melting silicates. Continued heating at temperatures in excess of 1210°C for longer periods of time produced dark green to black, glassy material which reflects the complete or nearly complete reduction of ferric oxides to ferrous oxide.

In another series of tests a reducing environment was provided by inserting a tray filled with lignite along with the sample tray into the furnace. Predictably, the specimens in the reducing atmosphere tended to become somewhat darker in color than those fired at the same temperature in an oxidizing environment. In the case of sample No. (2R) (Buck Hill, reducing environment), there was about a 40°C differential in attainment of the same dark color. This color change became evident beyond 980°C, as a probable result of a slightly higher ferrous oxide to ferric oxide ratio.

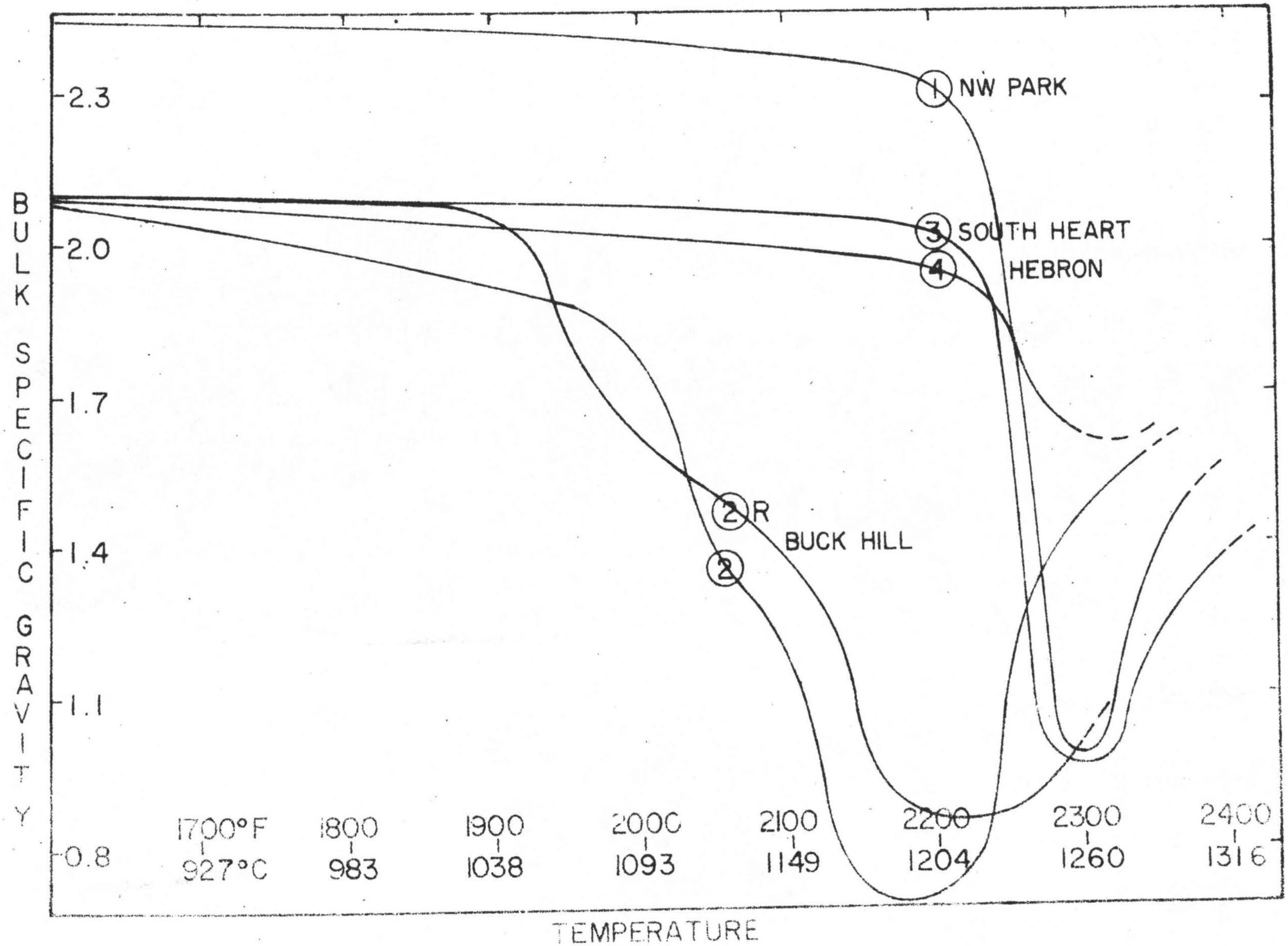
Specific Gravity Changes

The specific gravity measured is intimately related to the formation of cellular structure which results when the sediments begin to fuse. This measurement then, is the bulk specific gravity, which concerns exterior volume, and includes both sealed and open pores.

In most cases, the minimum bulk specific gravity was reached when the temperature was raised from 70 to 90°C beyond the point of initial fusion. Further increase in temperature generally caused an increase in bulk specific gravity (Fig. 6). At the highest temperatures (above 1,380°C) attained, the melted material became quite vitreous, and the pores decreased in size and increased in number, and finally fused to a solid glassy mass.

The samples exhibited different behavior with respect to bulk

Fig. 6.—Graph showing change in bulk specific gravity of some Tongue River Formation sediments with increasing firing temperature.


BULK SPECIFIC GRAVITY
2.3
2.0
1.7
1.4
1.1
0.8
1 NW PARK
3 SOUTH HEART
4 HEBRON
2 R
2
BUCK HILL
1700°F
927°C
1800
983
1900
1038
2000
1093
2100
1149
2200
1204
2300
1260
2400
1316
TEMPERATURE

specific gravity as the fusion range was approached. Sample No. (1) (NW Park) showed almost no decrease in bulk specific gravity beyond the observed initial fusing point until a temperature some 40°C greater (1,230°C) was reached (Fig. 6). The specific gravity then dropped sharply and increased only slightly upon firing at higher temperatures. Samples Nos. (2) and (2R) (Buck Hill) began to decrease in bulk specific gravity some 40 to 60°C before the observed melting point and continued to decrease to a minimum, then rose sharply with an increase in temperature. Samples No. (3) (South Heart) and No. (4) (Hebron) reacted in much the same way, showing a sharp increase in bulk specific gravity beyond the area of minimum specific gravity. The maximum decrease in bulk specific gravity (1.4) was exhibited by specimen No. (2R), and the minimum (0.8) by specimen No. (1).

Bloating Characteristics

The bloating property of a fused sediment results from the generation and expansion of gas from impurities in the mass when the material has been heated to incipient fusion, and is in a semiplastic state. At the melting temperature, surface tension operates to draw some of the melted material into the existing pores causing some of the generated gas to be retained. As the temperature is continuously increased the viscosity of the mass decreases to a point where the gas bubbles can easily break through the melted material, producing smaller sealed pore spaces, and fewer closed pores. This marks the end of the bloating phenomenon.

All sediments do not bloat or expand upon heating to elevated temperatures. Some are too refractory, and others melt over a narrow temperature range, forming a dense glassy mass. Sample No. (1) is a good example of a non-bloating sediment which fused without the formation of large pores (Plate I).

Samples No. (3) and (4) both showed a very narrow bloating range over approximately 40°C. Beyond this range the pore size decreased rapidly. Sample No. (2) showed the widest bloating range (approximately 95°C), and the largest pores (8 mm). All of the specimens tested had too narrow a bloating range, and with the exception of sample No. (2), were too refractory to be of commercial importance as lightweight aggregate.

Theoretical Firing Effects

In general, when a sediment is subjected to firing, some of the contained compounds break down, water vapor and other gases are evolved, and oxygen is taken into combination. Upon fusion a new variety of complex alkali, calcium, magnesium, iron, and aluminum silicates is formed. This process may conveniently be divided into a dehydration, oxidation, and vitrification stage.

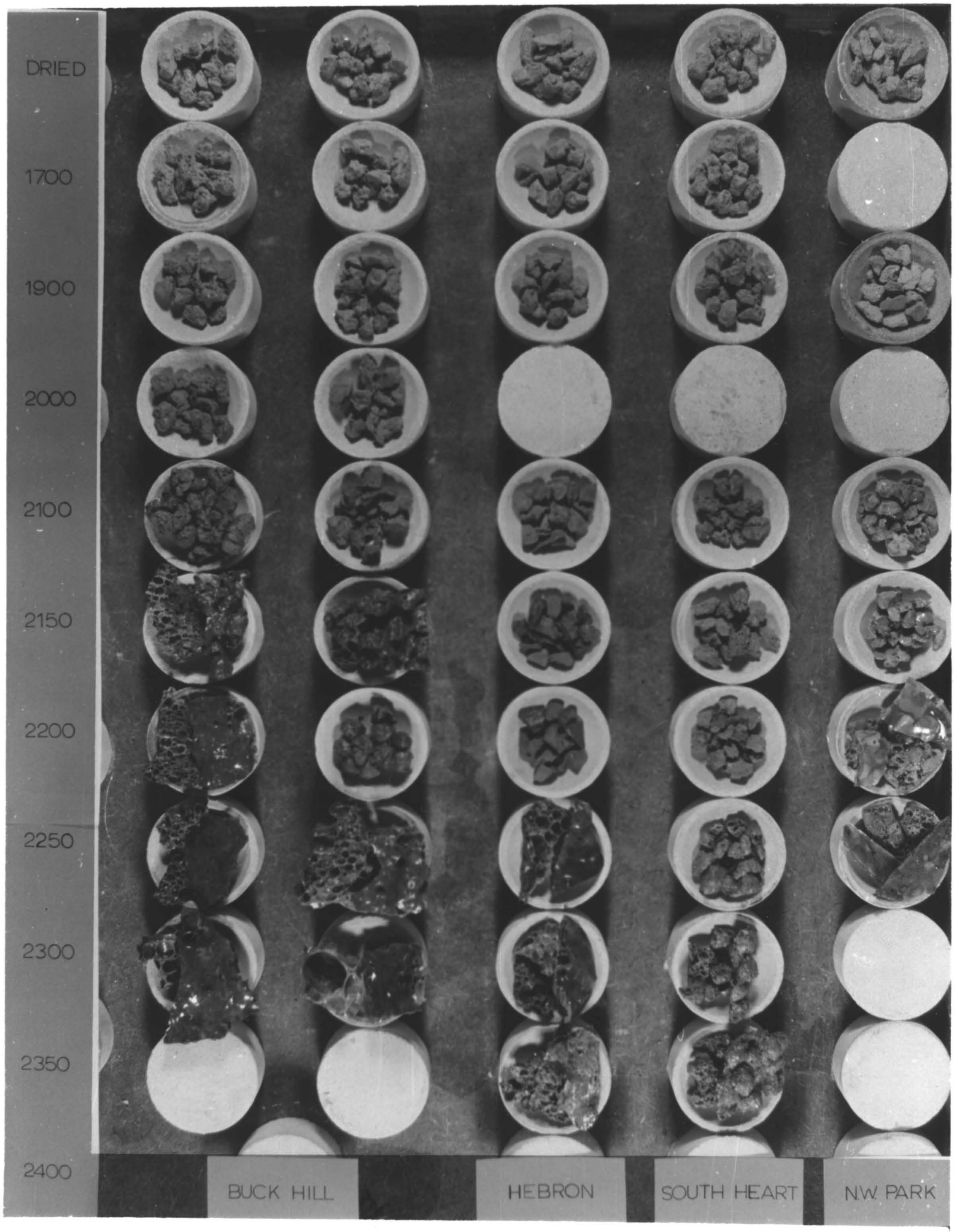
Dehydration-Oxidation Stage

The exact temperature boundaries of the three stages may vary with different sediments. According to McNamara (1945, p. 55), the dehydration range extends to about 600°C, and is overlapped by the oxidation range which extends between approximately 350-950°C. The dehydration phase is initiated by the expulsion of mechanically held water which reaches completion at a temperature of about 150°C. Chemically combined water may be evolved at temperatures as low as 100°C when gypsum is present. The greatest loss of weight takes place

PLATE I

EFFECTS OF FIRING ON SOME TONGUE RIVER FORMATION SEDIMENTS

Photograph shows the progressive change in shade and texture of sediments with increased firing temperature (°F). [Buck Hill (2H) on left side].


DRIED
1700
1900
2000
2100
2150
2200
2250
2300
2350
2400
BUCK HILL
HEBRON
SOUTH HEART
N.W. PARK

between 440–600°C as a result of loss of chemically combined water (McNamara, 1945, p. 55). At 600°C most of the hydrous minerals have lost their chemically combined water. According to Wilson (1927, p. 148), however, temperatures in excess of 750°C may be necessary to remove the last trace of chemical water.

The oxidation phase begins with the oxidation of easily ignited organic matter and sulfur (370°C), and continues until the last trace of carbon is burned out. It may overlap the vitrification phase. McNamara (1945, p. 57) states, that during this phase $CaCO_3$, $MgCO_3$, $FeCO_3$, FeS_2, $CaSO_4$, $FeSO_4$, and $Fe_2(SO_4)_3$ decompose. The sulfides oxidize to form sulfates. Sulfates are difficult to break down and dissociation may not occur until temperatures above 930°C are reached (Wilson, 1927, p. 155). Iron sulfates may be dissolved during the chemical hydration phase leaving a brown scum of oxide on buff-colored sediments after the sulfate has been dissociated.

Changes in physical properties also occur during this period. Clays which contain carbon will tend to be bleached as the carbon burns. Iron-bearing sediments deepen in color as they are heated to 950°C, becoming buff or red, depending upon the distribution and amount of iron oxide present. The clay material continues to lose weight, and becomes more porous as the carbon is burned and the carbonates, sulfides, and sulfates are dissociated. If quartz is present, its conversion to tridymite may cause expansion to take place in the mass. McNamara (1945, p. 54) states that calcium carbonate will begin to dissociate at about 600°C, and will accelerate to completion at 900°C, causing a strong fluxing action.

grade iron ores. Chemical tests by the writer, and others (Rogers, 1918, p. 9) indicate that the few Tongue River sediments studied range from about two to 10 per cent iron oxide, and average about five per cent iron oxide, calculated as Fe_2O_3. Coloration, however, is also dependent upon the dispersion and fineness of the iron oxides. In the vitrification range, the iron oxide dissociates (1,000°C), and under the proper conditions, may be reduced (Wilson, 1927, p. 162). The result is an increase of ferrous oxide in the form of magnetite, which is reflected in a darkening of the oxidation colors.

At very high temperatures (1,200-1,260°C), the alumina and silica present combine to form mullite, the stable high-temperature compound of alumina and silica. At temperatures above 870°C quartz is altered to the more stable form, tridymite, with an attendant increase in volume. Cristobolite may also begin to form at somewhat higher temperatures. At temperatures above 1,000°C, alumina may also begin to invert to corundum, the stable high temperature form. In the case of more complex systems, as represented by the Tongue River sediments, minerals such as diopside, cordierite, plagioclase, sillimanite, and perhaps, wollastonite and tremolite, would be expected to form in the range of these same high temperatures.

Fluxes

According to McNamara (1945, p. 94), a flux is any mineral which will lower the softening, fusion, or liquification temperature of the mineral assemblage. Therefore, flux is a relative term and does not refer to any particular class of substances. The effects of feldspars and calcium silicates in this connection have already been discussed

(p. 52). The occurrence of carbonate minerals in the sediments is, however, particularly significant. The fluxing action of calcite is about ten times that of an equal amount of feldspar. Small amounts of this mineral were added to some of the fired sediments, and the calcite tended to accelerate fusion of the sediments, and shorten the vitrification zone. Additions of gypsum tended to shorten the vitrification zone, also. In general, according to McNamara (p. 54), most minerals, with the exception of the alumina minerals and mullite, tend to act as fluxes toward the mineral mass during firing.

CONDITIONS NECESSARY FOR "SCORIA" FORMATION

Previous Work

As early as 1805, Lewis and Clark reported the occurrence of "pumice stone" and "lava", and related it to burning lignite beds. They not only recognized the process by which "scoria" was formed, but actually produced synthetic "scoria" by baking and melting samples of the parent sediment in a furnace (Reid, 1948; DeVoto, 1953). They also suggested spontaneous combustion as the most likely agency of ignition.

In 1874, Allen (p. 248-251) recorded a relatively accurate and thorough description of the variation in "scoria" types, and reported the existence of chimney-like mounds of "volcanic breccia". He also reflected on the effect of pressure from the large quantity of explosive gases presumably supplied by the burning of lignite beds. In a later article (1876, p. 210), Allen stated:

> The burning of such large masses of lignite must of course, especially when the beds have considerable thickness, produce an intense heat; yet the metamorphism here seen seems sometimes to be on too grand a scale to be the result of so limited a cause.

He did not, however, suggest any alternatives.

Although the formational process is perhaps not so simple as suggested by MacBride when he said (1883, p. 472), "The lignite beds furnish the fuel, the slow-paced erosion lays the fuel bare, spontaneous combustion supplies the torch, and the whole phenomenon is explained.", he did introduce the important factor of exposure as a necessity for the formation of "scoria". He also included diagrams which showed the undermining of overburden by burning lignite, and the subsequent collapse of that overburden.

Rogers (1918) described in detail the variations in metamorphosis to be expected, the simple oxidation effects, progress of burning into the subsurface, some relationships between overburden and burning, penetration of burning into the subsurface, distillation effects, and the action of combustion gases when combined with air during fracturing of the overburden. His work remains a classic on many factors related to the formation of "scoria".

In 1925, Dove (Leonard and others, 1925, p. 20) discussed the relationship between lignite thickness and expected "scoria" thickness, conditions which would extinguish fires, and the relationship of slow oxidation of lignite to thickness of overburden.

The article by May (1954) is particularily significant in that it clarifies differences in oxidation and reduction effects, and emphasizes the effects of chemical processes. He also describes and diagrams a typical cross-section of "clinker".

While the two excellent articles by Rogers (1918) and May (1954) have outlined the basic principals of "scoria" formation, the writer believes that the picture presented is (perhaps understandably) oversimplified and that the different conditions and types of "scoria" formation have not been understood, or at least, explained.

It is obvious, however, from the summary of previous investigations that a number of requisites are necessary for the formation of "scoria". They are: a suitable grade and thickness of combustible fuel; an overburden of alterable sediments or rocks; exposure of the fuel; and an agent of ignition. It is surprising to note, however, that in the two largest areas of natural burning lignite in North Dakota, which appear to possess these necessary factors, no appreciable amount of "scoria" has formed. The purpose of this part of the investigation is to determine the factors of "scoria" formation that are lacking in two presently burning lignite areas.

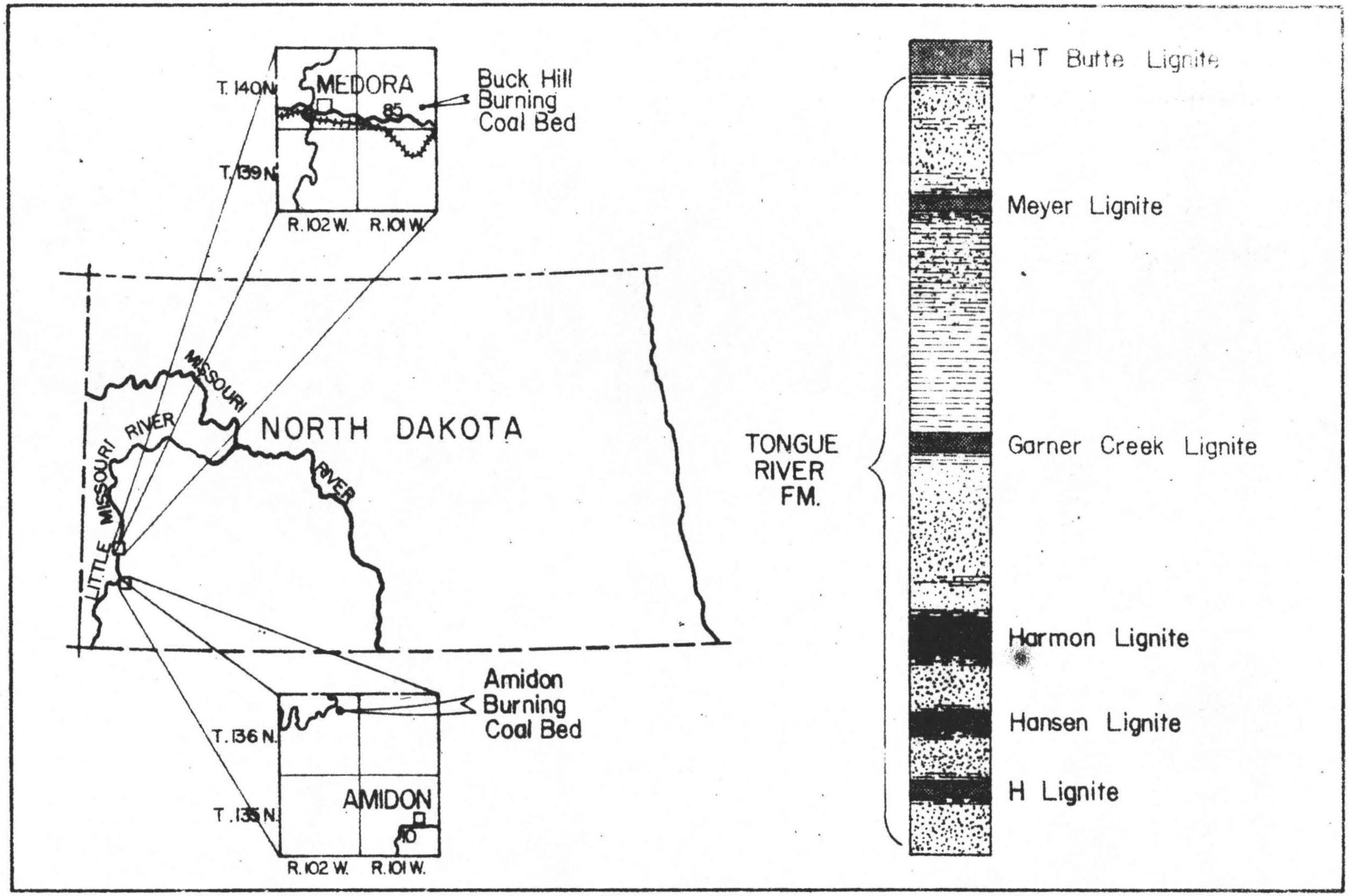
Two Presently Burning Lignite Areas

Location

A proportionally large amount of time during the field seasons was devoted to investigation of the "natural laboratories" provided by two large burning lignite beds in southwestern North Dakota. One of these, The Buck Hill Burning Coal Bed, is located in the South Unit of Theodore Roosevelt National Memorial Park, SW¼sec. 23, T. 140 N., R. 101 W., and the other, the Amidon Burning Coal Bed, is located approximately 11 miles northwest of Amidon, North Dakota, SE¼sec. 11, T. 136 N., R. 102 W. (Fig. 7). The Buck Hill "burn" occupies about six acres, almost twice the area of the Amidon "burn", which has burned at a more rapid rate. Active burning in the Buck Hill area was discovered in 1951, while the Amidon Burning Coal Bed area, according to Hares (1928, p. 31), has apparently been burning for considerably more than sixty years.

The actual "burn" in the Buck Hill area is an almost flat surface, bordered to the north by a ridge having relief of about 50 feet (Plate II, Fig. 2). It is bordered elsewhere around its periphery by "scoria" which formed during an earlier period. While the general relief of the "burn" area is less than five feet, several small buttes

Fig. 7.—Map showing the location of two presently burning lignite areas, and a generalized lithologic section of the Tongue River Formation with principal lignites.


MEDORA
T. 140 N.
T. 139 N.
R. 102 W.
R. 101 W.
85
Buck Hill Burning Coal Bed
NORTH DAKOTA
MISSOURI
RIVER
LITTLE MISSOURI RIVER
Amidon Burning Coal Bed
T. 136 N.
T. 135 N.
AMIDON
10
R. 102 W.
R. 101 W.
H T Butte Lignite
Meyer Lignite
Garner Creek Lignite
Harmon Lignite
Hansen Lignite
H Lignite
TONGUE RIVER FM.

do occur within it. The collapsed butte in the center of the burned area near its southeast border marks the area of initial discovery of ignition. Two other buttes less than 20 feet high are located in the southwestern corner of the pit. A small amount of "scoria" was found to have formed near the more westerly of these buttes in 1963. Burning is presently taking place along the ridge to the north; along a front moving in a northwesterly direction; and to the west in a narrow tongue, in the southwest end of the pit.

In the Amidon Burning Bed area the surface is more irregular, and it slopes towards the east from a centrally located high area (Plate II, Fig. 1). During the past three years, areas of active burning have occurred in the north and northwest end of the pit; sporadically along the front which faces towards the east, and in the southeast end. Small amounts of "scoria" have formed in the northern end of the pit.

Nature of "Scoria"

In the opinion of the writer, the minimal characteristics necessary to constitute "scoria" are cohesiveness through the action of melting or other "pyrometamorphic" induced activity, and a color change, if iron or organic compounds are present in sufficient quantity. In both burning areas there are small amounts of reddish to pinkish material which has the appearance of "scoria", but when handled, easily crumbles to material of ash-like consistency. The arbitrary decision not to classify this material as "scoria" is based on the observation that it weathers rapidly and would not be preserved long. Some "scoria", however, may not undergo a noticeable color change if the compounds which change color under the influence of heat are not present. In this case, the classification as "scoria" rests on demonstrable cohesiveness caused by "pyrometamorphic"-induced activity. "Pyrometamorphic"-induced activity may include, fritting, melting, ferric oxide cementation, and perhaps, authigenic growth of some minerals.

Investigation

During the summer field seasons of 1962 and 1963, numerous measurements of firing temperature were made in the two burning areas. Temperatures were measured by a chromel-alumel thermocouple, connected to a direct reading potentiometer by insulated chromel-alumel leads. Where penetration was necessary, a five-eighths inch I. D. pipe, six feet long, and capped by a point, was driven into the ground. The thermocouple and leads, insulated by two-hole ceramic insulators, were then lowered into the pipe, and the temperature was later read from the potentiometer. Standardization for this equipment, before and after the field seasons, indicated a variation of less than 5°C from known temperatures in the range of measurement.

In the hottest zone of burning gases, the results of some thirty measurements, indicates the maximum temperature range to be about 760-800°C in both burning areas; the maximum temperature recorded was 883°C. The highest temperatures were recorded within several inches of the burning material, apparently in the reducing zone. In contrast to temperatures measured higher up in the flames, these temperatures remained relatively constant. Temperatures measured more than a foot above the burning bed dropped off by more than 100°C, and fluctuated widely, probably as a result of drafting conditions. Measurements in the substrate, which were separated by two feet or more of sediments from the hottest burning areas, usually showed a temperature increase of less than 50°C from ambient temperatures.

While the writer believes that a temperature of about 900°C is maximum for these two areas at the present time, it is not to be construed that temperatures could not become higher at some future time, particularily at the Amidon Burning Coal Bed area. Conditions of improved air circulation and drafting might significantly increase the temperature in either area. The writer does believe, however, that melting temperatures for these sediments (1,040-1,150°C) can be attained under conditions of burning common to these two areas.

Conditions in "burn" areas

Nature of overlying sediments

Under experimental conditions with similar Tongue River Formation sediments (preceding chapter), it was found that reddening or darkening takes place between 810-870°C. Under mild reducing conditions, the same sediments attained the same coloration at slightly lower temperatures, and also tended to fuse at temperatures slightly lower than the same sediments in oxidizing conditions. Initial fusion, usually the first indication of cohesiveness, took place in a range between 1,150-1,260°C.

Considering the probability that effects of color change and fusion are accentuated and accelerated in samples of small size, it is obvious that temperatures which would produce significant amounts of "scoria" are, at present, rarely attained in the two burning lignite areas. As the maximum temperatures recorded in these two areas are very close to the minimal temperatures necessary to produce a color change, it is possible that "burns" of this type could produce considerable amounts of low-grade "scoria" with slight improvements in drafting, or other factors which would raise the temperature slightly.

It is thus clear, from these several lines of evidence, that the sediments overlying the burning areas are at least capable of being metamorphosed to "scoria". First, as indicated by the heating experiments, synthetic "scoria" can be formed from the sediments. Second, similar sediments have previously been metamorphosed to "scoria" in nearby areas. Third, as shown by later comparisons to numerous other samples and thin sections, these sediments fall within the range of composition of sediments which are known to have formed "scoria".

Character of lignite

A second possible reason for the lack of "scoria" in these two burning areas might be an insufficient thickness and (or) grade (relative quality) of lignite. "Scoria" has, however, formed over similar lignites in nearby areas. The Harmon Lignite (Fig. 7), which underlies the Amidon Burning Coal Bed area, has an average thickness of about 16 feet. The Buck Hill area is underlain by what appears to be the HT Butte Lignite, which has an average thickness in this area of about four feet. The Harmon is one of the thickest, persistent lignites in the southwestern part of the state, and even the bed underlying the Buck Hill area is thicker than some lignites which are known to have been involved in the formation of "scoria" elsewhere. The Harmon bed is a high grade lignite with a heating value of 6,062 Btu (Table 1).

The lignite underlying the Buck Hill area has a heating value of about 7,000 Btu (Table 1). Both of these lignite heating values are in the upper heating value range of lignites which have formed "scoria". It would appear then, that neither the heating value or thickness of the lignites, nor the composition of the overlying sediments will account for the lack of "scoria" in the two burning areas.

Significance of Overburden

"Scoria" crops out as a resistant capping or partial capping on buttes, ridges, and stream banks, and as an irregular bed of limited extension into the subsurface, below the summit of a ridge, butte, or stream bank. Typically, the extension of "scoria" into the subsurface is 25 feet or less, and while a penetration of fifty feet is not uncommon, "scorias" of greater extension are rare in the area of study. Further, the writer has found no "scoria" beds of large extent, as might be expected from "burns" of the Buck Hill or Amidon type, in western North Dakota. Several old collapsed "burns" of this type have been found, however, in which no "scoria", but some ash has been found.

The association of "chimneys", and the coke-like layers at the base of much of the persistent "scoria" afford a clue to the conditions of formation for "scoria". "Chimneys" are the more strongly metamorphosed zones of melted sediments which tend to remain as erosional remnants above surrounding, less strongly metamorphosed "scoria". The coke-like or "semi-coke" layers are composed of de-volatilized lignite and impurities (Table 1).

From the observations above, and the previous elimination of some other factors it would appear that the reason for the lack of "scoria" in the two burning areas probably lies in the thickness and nature of the overburden.

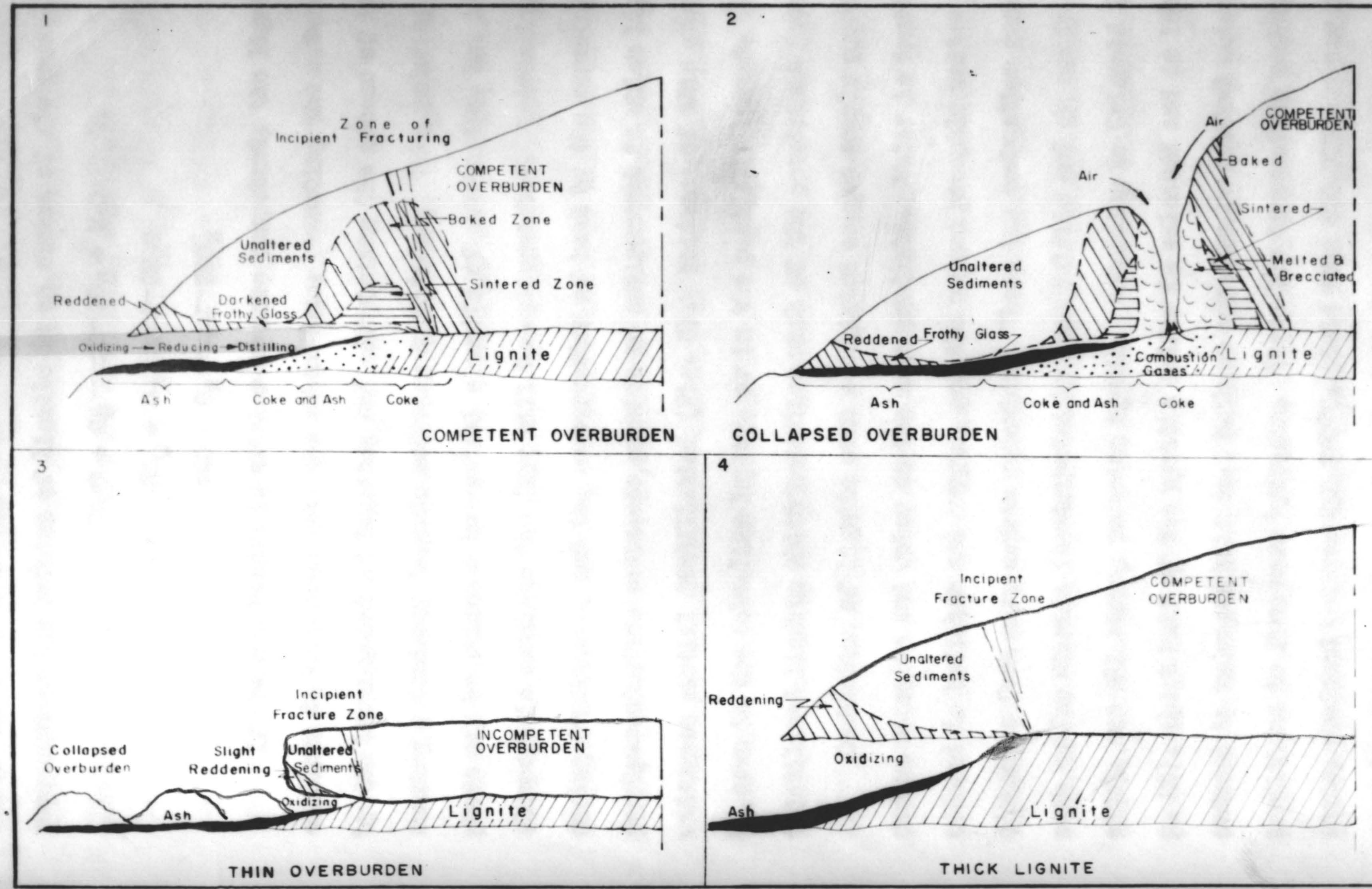
Model for the Formation of "Scoria"

Publications by Rogers (1918) and May (1954) have explained the formation of "scoria" as the result of chemical processes, as well as of thermal effects. From their theories, and personal observation, the writer would suggest the following model for the formation of "scoria".

Upon ignition, either spontaneously or through external agencies, fire spreads laterally along the exposed lignite and into the subsurface back of the outcrop. At this time the air supply is unrestricted, providing strongly oxidizing conditions for combustion. Burning, under these strongly oxidizing conditions, is usually limited in effect to occasional reddening of some of the sediments above, for several inches. As burning continues, a small cavern forms in place of the burned out lignite. At this point, the overburden, if relatively thin and incompetent (probably less than 20 feet), will tend to collapse in thin, vertical slabs, exposing more lignite to the atmosphere (Fig. 8, dia. 3). Burning takes place in a continuously oxidizing environment, and the effects on overlying sediments, if any, are caused by conduction of heat from the burning lignite, and simple oxidation of iron compounds.

Decomposition of lignite starts at about 200°C, with loss of oxygen in the form of water, CO, CO_2, and organic compounds. The hydrocarbons tend to form aldehydes, and these in turn form formaldehyde (CH_2O), at low combustion temperatures. In an excess of air the

Fig. 8.—Model of conditions leading to the formation of "scoria".


1
Zone of
Incipient Fracturing
COMPETENT
OVERBURDEN
Baked Zone
Unaltered
Sediments
Sintered Zone
Reddened
Darkened
Frothy Glass
Oxidizing — Reducing — Distilling
Lignite
Ash
Coke and Ash
Coke
COMPETENT OVERBURDEN
2
Air
COMPETENT
OVERBURDEN
Baked
Air
Sintered
Unaltered
Sediments
Melted &
Brecciated
Reddened
Frothy Glass
Combustion
Gases
Lignite
Ash
Coke and Ash
Coke
COLLAPSED OVERBURDEN
3
Incipient
Fracture Zone
INCOMPETENT
OVERBURDEN
Collapsed
Overburden
Slight
Reddening
Unaltered
Sediments
Oxidizing
Ash
Lignite
THIN OVERBURDEN
4
Incipient
Fracture Zone
COMPETENT
OVERBURDEN
Unaltered
Sediments
Reddening
Oxidizing
Ash
Lignite
THICK LIGNITE

formaldehydes form carbon dioxide and water. The generalized equations representing the burning of lignite in an excess of air are:

$$CH_2O + O_2 \rightleftharpoons CO_2 + H_2O$$

$$2H_2 + O_2 \rightleftharpoons 2H_2O$$

$$2CO + O_2 \rightleftharpoons 2CO_2$$

If the overburden is thicker or more competent, the lignite will continue to burn back into the subsurface, extending the cavern formed by the burning-out of lignite, and restricting the access of air, causing a tendency towards reducing conditions. This reducing atmosphere may be enhanced by partial slumping of overburden, but if slumpage is complete the fire will be extinguished. Increasing reducing conditions, and the conservation of heat by the surrounding, poorly-conductive sediments, provide an environment in which lignite undergoes partial distillation (Fig. 8). Evidence of this process may be seen in the coke-like layers, or in the partially burned, but devolatilized lignite which underlies much of the persistent "scoria".

Combustion of lignite with restricted oxygen supply produces carbon monoxide and water as the main products. Water is immediately reduced to hydrogen and oxygen, and the oxygen promptly unites with carbon to form more carbon monoxide. These two combustion gases, along with sulfur dioxide (contributed by iron sulfide and gypsum in the lignite), are all strong reducing agents. According to Griswold (1946, p. 20), about half of the pyritic sulfur is released and is immediately reduced to hydrogen sulfide. Methane may also be cracked under these conditions to form more hydrogen. These low temperature combustion gases, produced between 450-700°C, yield from 800-900 Btu per cubic foot (Griswold, 1946, p. 26). Partial fusion accompanies decomposition, and the entire mass of original lignite becomes semi-coke-like in appearance. The series of generalized end equations which represents burning under these reducing and distilling conditions is:

$$2CH_2O + O \rightleftharpoons 2CO + 2H_2O$$

$$C + CO_2 \rightleftharpoons 2CO$$

$$2C + O_2 \rightleftharpoons 2CO$$

$$CH_4 \rightleftharpoons C + 2H_2$$

$$FeS_2 + O_2 \rightleftharpoons FeS + SO_2$$

This potent mixture of combustion gases moves upward through interstices and fractures in the sediments, transmitting heat by contact, rather than by conduction. Heat from the combustion gases may be great enough to melt the first few inches of sediment or rock to a frothy glass. Rapid heat loss results in a gradation upward from simple melting, to fritting, and finally, to baking without melting. The gases also tend to reduce oxidized elements to lower valence forms. Hydrous iron oxides are reduced to ferrous compounds in melted material, and to magnetite, as the gases tend to lose reducing capacity in higher zones. With continued migration, the hydrogen and carbon monoxide oxidize to water and carbon dioxide which retain enough heat to bake the sediments and oxidize iron compounds. The reduced iron compounds contribute dark coloration to the metamorphosed material, and the reddish and pastel colors are produced by oxidized iron compounds and organic bleaching.

As excavation continues beneath the overburden by burning-out of lignite, structural resistance to collapse is eventually exceeded, and the overburden yields through fracturing. These fractures provide avenues for rapid access of air, and it is probable that accumulated combustion gases and the newly supplied oxygen combine at a very high reaction rate, providing heat to fuse rock for many feet along the fracture (Fig. 8, dia. 2). Upon melting, some of this material may flow into the fracture, and in combination with collapsed rock fragments, clog the opening. Thus, the gases are diverted into other fractures to act on an increasing volume of material. These strongly fused and brecciated fracture zones are often preserved as erosional remnants ("chimneys") above the level of less resistant "scoria".

After initial exhaustion of the accumulated combustion gases, the fractures become stacks over the fire, exhausting fire gases to the atmosphere and furnishing avenues through which air can reach the fire. A low pressure area develops over the fire, caused by expanding fire gases escaping through crevices to the surface. These convection-current stacks induce airflow into the fire area from lateral openings around the outcrop. The fracture itself may also act as ingress and egress at the same time. In such cases, hot gases issue from the center of the opening, while air enters around the periphery (Griffith and others, 1960, p. 12). The same fracture may also act as an avenue of entrance in one area and an outlet in another.

The thickness of the overburden determines the height of the stacking fracture. Since, according to Griffith, Magnuson, and Toothman (1960, p. 13), a higher stack produces a stronger draft, it is assumed that a break through deep strata provides more ventilation than one through shallow strata. This action probably contributes to the high degree of metamorphic effect typical of thick outcrops. Whatever the specific conditions, the fire continues to propogate under-ground by creating new breaks to the surface until the overburden became too thick to yield by fracturing.

Therefore, the lack of "scoria" in the two areas currently burning is apparently due to an insufficient thickness or competence of overburden. In the Buck Hill area, the overburden averages about six feet in thickness, and tends to collapse in narrow slabs with only slight excavation produced by the burned out lignite (Fig. 8, dia.); Plate II, Fig. 6). The thermal effects, if any, are a result of limited conduction of heat from burning, underlying lignite to the overlying sediments, in a continuously oxidizing atmosphere. As the present combustion temperatures in the two areas are below those necessary to form "scoria", it would obviously not be expected to form under these conditions. Beneath the larger butte in the southwest corner of the pit, however, a small amount of "scoria" has formed. Here the overburden is from 15 to 20 feet thick, which must be very near the minimal thickness necessary for structural competence to permit distillation, and allow gaseous transfer of heat to the surrounding sediments.

The minimal thickness of overburden necessary to promote formation of "scoria" in any area varies with the structural competence of the overburden, and the thickness of the underlying lignite. Structural competence is dependent on variables of texture, composition, and cementation of the overburden.

The same general conditions present at the Buck Hill area exist over much of the Amidon Burning Coal Bed area. To the west, however, the overburden thickens (Plate II, Fig. 1), and it is in this area that small amounts of "scoria" have formed. Deep collapse fractures

PLATE II

EFFECTS OF BURNING LIGNITE ON OVERLYING SEDIMENTS

Fig. 1.—View of the Amidon Burning Coal Bed (Fig. 7) looking northwest. Picture shows the thicker overburden encountered to the west.

Fig. 2.—View of the Buck Hill Burning Coal Bed (Fig. 7) looking southwest. Picture shows the large extent of the collapse area and the thin, relatively flat overburden.

Fig. 3.—Large cavern formed by burning of the Harmon Lignite in the Amidon Burning Coal Bed area. Cavern is about six feet in height and has burned about 20 feet in the subsurface.

Fig. 4.—Large vertical fracture in the thick overburden at the southwest end of Buck Hill Burning Coal Bed. Thicker overburden, and better drafting conditions in the fracture have led to the formation of small amounts of "scoria" along the fracture.

Fig. 5.—Large cavern formed by burning of the thick Harmon Lignite in the southeast end of the Amidon Burning Coal Bed.

Fig. 6.—Measurement of temperature in the Buck Hill Burning Coal Bed. Thermocouple (circle) and leads shown in the foreground. Picture shows the vertical slabs of thin collapsed overburden which slump forward into the Buck Hill "burn" where undermined by burning lignite.

Fig. 7.—Exposed HT Butte Lignite at location 17 (Fig. 3). Handle of entrenching tool (arrow) at extreme left of picture shows the full thickness (6 feet) of the lignite. Line of sample bags along low bank in the background indicates the decreasing thickness of lignite with increasing thickness of ash leading to the "scoria" outcrop at the far right of the picture. The lignite has burned back about 25 feet into the subsurface from the "scoria" outcrop.

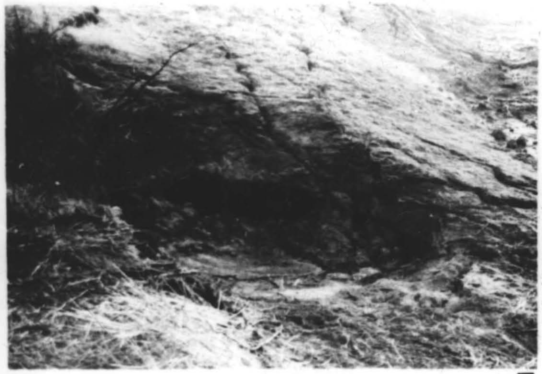
Fig. 8.—Large, "scoria"-capped butte located near the Little Missouri River in the Marmarth area (T. 134 N., R. 105 W.) showing the thick, white multiple ashes which are characteristic of the T-Cross Lignite. At least four ashes may be seen in the butte at closer distance. The thickest ash averages about four feet. The "scoria" appears to be about 60 feet thick.

1

2

3

4



5

6

7

8

indicate that the overburden thickness may be 25 feet, but even here "scoria" is rare. In this case, the great thickness of the Harmon Lignite produced very large caverns upon burning (Plate II, Fig. 3 and 5), which provide relatively unrestricted air supply and oxidizing conditions until overburden collapse occurs (Fig. 8, dia. 4). Once again, the slight thermal effects would be produced by conduction of heat from the burning lignite, and simple oxidation. As the lignite under much of this thick overburden has not been burning actively for some time; and as the few fires burning in large caverns are periodically extinguished by overburden collapse, it does not seem likely that extensive "scoria" will form there in the future. In any case, a very thick, competent overburden will be necessary to sustain the extended excavations until distillation of lignite could take place.

MODES OF "SCORIA" FORMATION

As implied in the previous chapter, there are a number of different conditions which produce deposits of "scoria" which vary in grade, extent, and manner of occurrence. The diversity in conditions which result in these varying deposits of "scoria" has not been generally recognised in previous literature.

The first mode of formation is typified by conditions present in the Buck Hill area. The exposed lignite is overlain by a relatively uniform, thin overburden. The overburden is too thin or incompetent to sustain extended caverns in the underlying, burning lignite. Collapse of overburden prevents the establishment of prolonged reducing conditions, and the burning environment remains oxidising (Fig. 8, dia. 3). Deposits of this nature are characterised by occasional, small amounts of low grade "scoria" in large pits of collapsed overburden.

A variation of this same mode of formation is exhibited in the Amidon Burning Coal Bed area. In this case, while the overburden may be relatively thick, the extreme thickness of the lignite prevents restriction of air, as the thick lignite burns out to form large, nonrestrictive caverns (Fig. 8, dia. 4). As the air supply is not restricted, the atmosphere remains largely oxidising, and the effects of combustion on the overlying sediments are essentially the same as in the Buck Hill type of "burn".

A second mode is seen in the occurrence of low-grade "scoria" in the lower one-third of the bluffs along the Little Missouri River at Theodore Roosevelt National Memorial Park. This mode of occurrence is characterized by relatively continuous outcrops of low-grade "scoria" beneath a thick overburden of approximately 100 feet or more of sediments. The overburden is so thick that it has neither fractured nor collapsed, and thus the extension (as far as may be checked) of "scoria" into the subsurface is less than 25 feet. The lack of overburden collapse and fracturing, the low grade of metamorphism, and the probable limited extension into the subsurface, suggest that the firing atmosphere was essentially oxidizing. It would appear that better drafting conditions, such as might be expected along the course of a river, may have been the factor which was sufficient to raise the temperature of firing to that necessary to produce the low-grade "scoria". Thicker, and higher grade lignite may also have been a factor in raising the temperature by the slight amount necessary to produce low-grade "scoria" consistently.

The third mode of formation is characterized by the very extensive, and persistent HT Butte "Scoria", which occurs throughout much of 2,000 square miles. This "scoria" either caps, or lies within, the upper one-fourth of the terrace labeled No. 4 by Laird (1950, p. 11), in the area of study. Conditions responsible for the formation of this type of deposit would necessarily have to be both uniform and persistent. It is obvious that a relatively thick, uniform, and extensive lignite, such as the HT Butte Lignite, would be a necessary factor. It is also apparent that the overburden at the time of formation, would have had to have been in excess of 20 feet in thickness to provide the structural competence necessary for the maintenance of distilling conditions which produced the extreme thicknesses, and varied metamorphism of this "scoria". An optimal maximum thickness must have been another necessity. If the overburden were very thick, probably 80 to 100 feet, it would not yield by fracturing or, at least, the higher sediments would seal the cracks which resulted from fracturing in the overburden directly overlying the burned out lignite. In this case, the fire would be extinguished eventually, as a result of the decreasing supply of air in the extended and restricted cavern in the underlying lignite. Under these non-distilling conditions, only low- to medium-grade "scoria" would be formed, a characteristic not in accord with field observation. A maximal thickness to permit fracturing, in the magnitude of 100 feet or less, is somewhat hypothetical, but the writer has observed overburden collapse under similar conditions in overburden of at least 50 foot thickness. Griffith, Magnuson, and Toothman (1960, p. 14), in their study of fire control in coal formations, have suggested that the maximum overburden thickness would be 60 feet or less, to provide breaks to the surface. Some of the thickest "scorias", howwver, have a thickness of about 80 feet.

The uniform conditions required for this mode of formation would most likely have been met during the cutting of Terrace No. 4. According to Fetter (1965, p. 21), this cut terrace formed a former strath of many square miles from Marmarth, North Dakota, north, along the Little Missouri River beyond the "Big Bend". The flat, plateau-like surface would have provided ideal conditions for the formation of "persistent scoria" when the surface was reduced to within approximately 100 feet of the underlying HT Butte Lignite. The only necessary factors remaining would then be dissection to provide exposure, and subsequent spontaneous ignition. Other "persistent scorias" are probably also related to cut terraces, or possible erosion surfaces. This mode of formation is characterized by persistence, frequent high-grade metamorphism, "chimneys", extreme thickness, and often, pseudocolumnar jointing.

A fourth mode of formation is characterized by the small, isolated "scoria" outcrops of diverse nature found in the eastern part of the "scoria"-bearing area (Fig. 1A) where other modes of formation are relatively uncommon. This mode of formation may occur throughout the "scoria"-bearing area, however. Conditions of limited exposure of lignite and overburden favor this mode of formation. This mode of formation often occurs in relatively undissected areas along drainage courses where a limited amount of lignite is exposed. The type of deposit and variety of "scoria" formed is dependent on variations in topography. If the overburden above the lignite is thin, only slightly metamorphosed "scoria" will result. If the burning lignite underlies an overburden of considerable area and appropriate thickness, all varieties of "scoria" may occur, from the lowest to most highly metamorphosed grades. This mode of formation may also occur under conditions where discontinuous lignites burn out under overburden or where the overburden thickens and thins irregularily over burning lignite. Any combination of these variable factors may also lead to this mode of occurrence.

The isolated and limited "scoria lump" deposits in the Glen Ullin area and in the area north of Sentinel Butte are similar in appearance, and may have the same mode of formation, but are more likely the strongly metamorphosed erosional remnants of "persistent scoria" formed on an old eroded upland surface. Thus, these isolated "scoria" outcrops of limited extent, and varied nature, may not be genetically related, even though similar in appearance.

Another unusual condition related to the formation of "scoria" is that of multiple burning, a condition apparently first mentioned in the literature by Leonard (Leonard and others, 1925, p. 6). The thickest "scoria", typified by deposits in Sentinel Butte, and Scoria Point (Theodore Roosevelt National Memorial Park, Loc. 15, Fig. 3), are formed by the burning of a number of separate lignite beds or stringers. At Sentinel Butte, at least six ash or "semi-coke" layers can be found (Plate VIII, Fig. 1), and Scoria Point contains at least three distinct ash and "semi-coke" layers. It appears likely that ignition originates in the lowest lignite, then when fracturing occurs, the combustion gases travel along this path and ignite the next overlying lignite. It is also possible that closely spaced lignites could be ignited directly by the flames from an underlying, burning lignite. "Scorias" formed by this process may have a thickness greater than 80 feet, as at Sentinel Butte (Plate VIII, Fig. 1).

Age of Formation

Theoretically, there is no reason why "scoria" should not have formed as soon as the lignites in the Fort Union Group were exposed by erosion. If this is true, it is likely that the "scorias" higher in the section are the older. According to Petter (1956, p. 45), extensive erosion of the Fort Union Group began in Eocene time in the area of study. He concludes, as do Hares (1928, p. 52), Benson (1952,

p. 53), Petter (1956, p. 33), and the writer, that the formation of some of the "scoria" began at least as early as Eocene time. In support of this, Hares (p. 52), Benson (p. 53), and the writer, have found "scoria" fragments in the basal conglomerates of the White River Formation of Oligocene age which indicate that "scoria" had been formed prior to White River time. As first observed by Petter (p. 45), the basal marl beds of the White River Formation on Sentinel Butte contain fragments of "scoria", and are also stained by streaks of red iron oxide which indicate that the White River beds were deposited on an eroded "scoria" surface. The many observations by numerous investigators of "scoria" containing baked till, and the present occasional formation of "scoria" in burning areas, attest to the fact that "scoria" has formed in recent times also. The writer therefore believes, in agreement with the previously mentioned authors, that formation of "scoria" began with exposure and subsequent burning of lignite in Eocene time, and has continued to the present day.

PETROGRAPHIC CLASSIFICATION OF "SCORIA"

Introduction

The detailed lithologic character of "scoria" has been studied by few authors. In even the more detailed studies, the investigators have, understandably, confined their studies to the coarser, metamorphosed sandstones, and to recrystallized "slags". This part of the study is devoted to detailed investigation of the petrographic and mineralogic character of all known varieties of "scoria" from North Dakota. A discussion of the term, "scoria", and a summary of classification of varieties will be found near the end of this chapter.

Previous Work

Perhaps the earliest microscopic study of "scoria" in the United States was that of Bastin in 1905. In 1907, Arnold and Anderson briefly mentioned the lithologic character of some metamorphosed shales in California. Rogers' study, published in 1918, remains a classic concerning most aspects of "scoria" in the western lignite-bearing area. The work of Lonsdale and Crawford in 1928, follows much the same pattern as that of Rogers'. Their study concerned baked and melted sediments in Texas. Both of these publications were somewhat limited, however, in that investigation was slanted to the lithologic and mineralogic character of baked sandstones and recrystallized slags. The latest investigation is that published in 1964 by Lydon, which includes some mineralogy and chemistry of "silicate slag" from California.

Present Investigation

The initial phase of study was begun by the preparation of some 160 petrographic thin sections of "scoria". As many of the specimens are very friable, more than one-third of the thin sections required impregnation by heating at low temperature in Lakeside #70 for an extended period of time. Microscopic study of the fine-grained rocks was limited due to the minute size of individual grains, and the frequent opacity, contributed by iron oxide staining and carbonaceous material. Estimates of mineral content in the coarser, metamorphosed, siltstones and sandstones were made by point count analysis and recorded on a digital counter. Difficulties were encountered in this approach as the most common minerals, quartz, sanadine, untwinned plagioclase, orthoclase, cordierite, anhydrite, and gypsum, all have a similar appearance under the microscope. Identification was facilitated by using a binocular petrographic microscope with a pinhole objective in one eyepiece holder to determine sign rapidly. Mineral identification was further hampered by the frequent existence of silica glass of unknown and variable index of refraction, surrounding individual grains. Either 500 or 333 point counts were made on each thin section, depending on the estimated reliability of identification. According to Van Der Plas and Tobi (1965, p. 87-90), the former number should result in about a four per cent reliability at the 95 per cent confidence level and the later number of points, in a five per cent reliability at the same confidence level. This study was further supplemented by analysis of 22 stained sections. These sections were prepared by etching a rock slice, mounted on a petrographic slide, in hydrofluoric acid fumes, then staining alternately with sodium cobaltinitrite and Eosine "B". Staining materially aided the identification of quartz, chert, potash feldspar, and plagioclase. In all, 63 sections were subjected to point count analysis. Data for selected specimens are presented in Tables 6 and 7. Numerous isolated mineral grains were hand-picked, and studied by the use of immersion liquids, to determine their optical properties. The plagioclase in five thin sections was also determined by universal stage investigation. This information helped to determine the range of composition of feldspar in these specimens.

X-ray diffraction studies of some 40 specimens helped to determine petrographic composition and change, especially in the fine-grained, and melted "scoria". All specimens were prepared as powder packs. Whenever necessary, the clay minerals were further treated for X-ray study by heating, glycolation, and acid digestion.

Carbonate content was determined by volumetric analysis, and calculated as calcite. Carbonate may appear, however, in various forms, the most common of these being calcite, dolomite, and siderite. The calculation as calcite is for the purpose of comparison, adjustments would have to be made on each individual specimen as determined by the estimated content of each kind of carbonate. In thin sections, the determination of the type of carbonate is often rendered difficult as a result of fine size, and hematitic staining. Data for 32 specimens appears in Table 5.

Several semi-quantitative analyses were carried out on different types of "scoria" to determine the iron content. Samples were decomposed by hydrofluoric acid, and iron was determined by titration with potassium permanganate.

Table 5.--Volumetric Analysis of Carbonate in "Scoria"

Location	Sample No.	"Scoria" Variety	Calculated % $CaCO_3$
Loc. 12	12a	Baked Sandstone	2.7
Loc. 19	19	Baked Columnar Sandstone	23.3
Loc. 19	19j	Baked Sandstone	4.4
Loc. 32	32b	Baked Limestone	58.8
Loc. 34	34e	Vitrified Laminated Shale	0.0
Loc. 40	40a	Baked Limestone	55.3
Loc. 40	40f	Baked Shale	1.3
Loc. 40	40g	Baked Shale	0.8
Loc. 40	40i	Recrystallized Slag	0.0
Loc. 53	53b	Baked Limestone	46.3
Loc. 54	54a	Baked Sandstone	13.9
Loc. 55	55a	Baked and Vitrified Sandstone	44.8
Loc. 55	55f	Baked Shale	13.9
Loc. 55	55j	Baked Mudstone	13.6
Loc. 66	66a	Baked Mudstone-Porcellanite	14.8
Loc. 66	66d	Porcellanite	24.2
Loc. 66	66e	Porcellanite	13.5
Loc. 77	77a	Porcellanite	2.7
Loc. 87	87c	Baked Sandstone	2.3
Loc. 89	89b	Baked Mudstone	11.7
Loc. 99	99bs	Baked Sandstone	2.7
Loc. 99	99br	Glassy Slag	1.3
Loc. 106	106a	Baked and Melted Sandstone	4.8
Loc. 110	110a	Vitrified Shale	0.0
Loc. 125	125b	Baked Columnar Sandstone	10.9
Loc. 125	125c	Baked Columnar Sandstone	7.9
Loc. 10	310c	Porcellanite	14.1
Loc. 350, sec. 33, T. 141 N., R. 101 W.	350	Baked Columnar Sandstone	9.7
Loc. 360, sec. 33, T. 141 N., R. 101 W.	360	Baked Columnar Sandstone	12.1
Loc. 17	HTs	Parent Sediment	2.7
Loc. 17	HTr	Artificially Baked Mudstone	2.0

Information derived from these data suggests that "scoria" can be subdivided into the following general groups (listed in approximate order of increasing metamorphism): baked shale and baked mudstone, baked limestone, baked sandstone, porcellanite, vitrified siltstone, vitrified laminated shale, glassy slag, and recrystallized slag.

Petrography

Baked Shale and Baked Mudstone

Baked shales and mudstones are by far the most abundant type of "scoria", as clay and silt, by the observed cyclic nature of their deposition in the area of study, most often directly overlie the lignite. These rocks typically reflect the composition of the parent sediments rather closely, and differ from them mainly in color, state of dehydration, cohesiveness, and texture. The color of these rocks is perhaps their most striking characteristic. The prevailing colors are salmon pink, red, reddish orange, and reddish brown. "Colors" for this material do, however, range from grayish-white to gray-black. The white shales and mudstones are relatively rare, and are confined to the uppermost Sentinel Butte Member, or basal Golden Valley Formation. They are apparently the result of baking kaolinite clays which are deficient in iron compounds. Some of the shales and mudstones are mottled in red, yellow, green, and black. Perhaps the most common color range of the baked shales is from moderate reddish orange (10 R 6/6) to moderate reddish brown (10R 4/6), as represented in the Munsell system. The colors mainly reflect the content and state of contained iron compounds, the red and pink colors being due to hematite staining, and the darker colors resulting from partly reduced, ferrous iron compounds.

In thin sections, the hematite staining may be particularily pronounced. Some sections may be rather heavily stained by hematite over 90 per cent of their area, but chemical analyses by the writer, and other workers (Rogers, 1918, p. 9; Lydon, 1964, p. 101), indicate that the hematite content is usually less than 20 per cent. Two specimens analysed by the writer, contained about eight per cent hematite, even though they were moderately reddish brown in color, and intensively stained in thin section. Hematite occurs not only as a pervasive stain, but also in the form of minute scales, and as "blebs" formed around clay and carbonate minerals. The "blebs" may be rather distantly disseminated throughout the specimen, but they still present the illusion of uniform reddish color. Magnetite also occurs in small amounts in most of the specimens, and is particularily common as an inclusion in other mineral grains. The iron for these compounds is supplied by limonitic material in the parent sediments, and from decomposition of biotite. Biotite relicts may occasionally be observed which are almost completely replaced by hematite. It is also possible that some of the limonitic material was originally formed by the decomposition of biotite, as biotite in the unaltered form is not particularily common in the lower part of the Sentinel Butte Member and the upper part of the unnamed member.

The shales and mudstones respond readily to heat, losing their original texture and becoming cohesive. Cohesiveness results from hematite cementation, and the growth of tiny interlocking microlites of plagioclase and muscovite-sericite. There is generally no evidence of direct melting or fritting, but the clay minerals, carbonate,

PLATE III

BAKED, FINE-GRAINED "SCORIA"

Fig. 1.—Baked mudstone (55i, Loc. 55) showing the slickenside surface. (One inch reference grid.)

Fig. 2.—Porcellanite (66l, Loc. 66) showing the hair-line sharp change in shade, fine texture, and semi-conchoidal fracture of the variety. (One inch reference grid.)

Fig. 3.—Photomicrograph of a baked mudstone (UND 1219, Loc. unknown) showing lineation of hematite "clots" and micaceous minerals parallel to slickenside surface (extreme lower right corner). Matrix composed of clay minerals, hematite, sericite, quartz and plagioclase.

Fig. 4.—Photomicrograph of a porcellanite (310c, Loc. 10) showing texture, and disseminated hematite "blebs" which contribute to the pastel red color. Small white grains are plagioclase. Matrix of carbonate, silica glass, clay minerals, and sericite.

Fig. 5.—Photomicrograph of a baked mudstone (15a, Loc. 15) showing small tridymite paramorphs, and larger, shard-like oligoclase grains.

Fig. 6.—Photomicrograph of a baked mudstone (55e, Loc. 55) showing texture, and slight fusion of larger plagioclase grains. Matrix of clay minerals, sericite, and carbonate. Dark grains are hematite.

Fig. 7.—Photomicrograph of a baked mudstone (89b, Loc. 89) showing transition zone between a very fine-grained hematitic band (upper) and a coarser, silt-sized band. Large white, shard-like grains are plagioclase in a strongly hematitic-stained matrix.

Fig. 8.—Photomicrograph of a baked limestone (32b, Loc. 32) showing extremely fine-grained texture of the carbonate, and the mixed carbonate (mainly siderite) and clay mineral matrix.

All photomicrographs taken with polarizers crossed. Bar scale shows size.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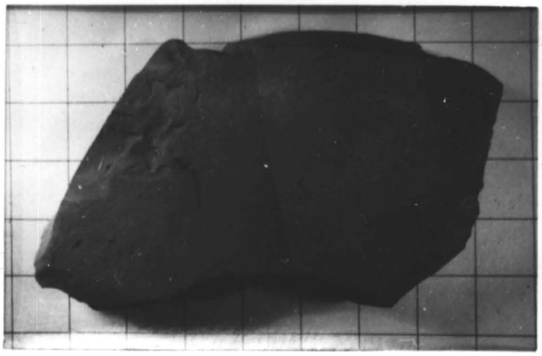
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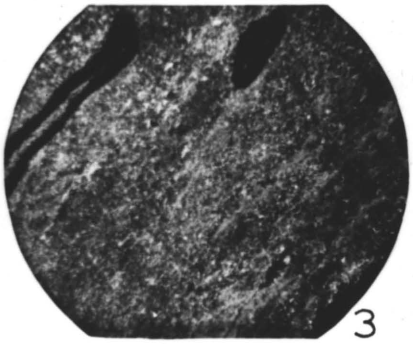
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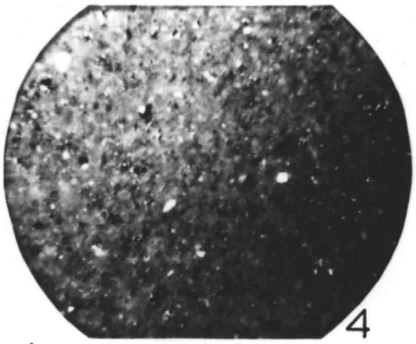
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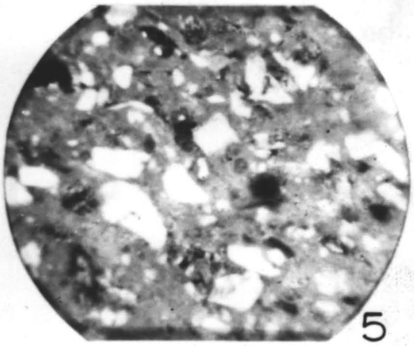
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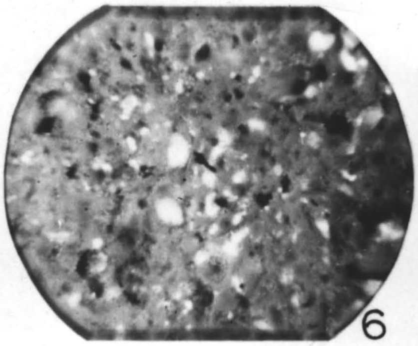
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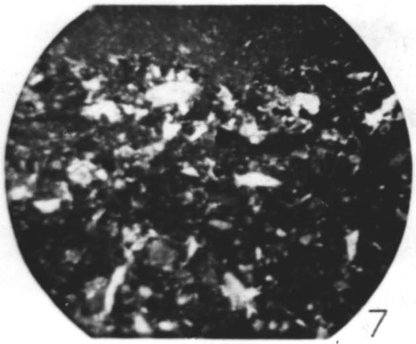
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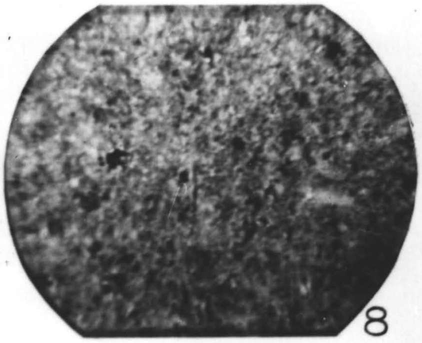
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sericite, and iron compounds undergo metamorphism, even at these relatively low temperatures. Direct evidence of these changes is only rarely observed under the microscope, but can be seen to take place when these varieties are compared to parent sediments by X-ray diffraction methods.

One of the great difficulties in determining the changes which take place in "scoria" has been in attempting to correlate the parent rock with the metamorphosed product. In the more highly metamorphosed varieties of "scoria", correlation has been nearly impossible, but some specimens of less strongly affected "scoria" have been correlated with reasonable accuracy. Several baked shales and attached parent sediments were examined by both optical and X-ray diffraction methods to determine the mineralogic changes which took place. X-ray diffractograms indicate that the limonitic material in the sediment oxidizes to hematite in the baked rocks, and that montmorillonite, sericite, and carbonate combine to form a more basic plagioclase. The most common plagioclase in the parent sediment is basic oligoclase, which has a variable, but average composition of about Ab_7An_3. The baked sediments, however, show a more pronounced bi-modality of plagioclase on X-ray diffractograms with increasing metamorphism, and a tendency towards shifting of X-ray "peaks", indicating secondary development of plagioclase ranging from Ab_6An_4 to Ab_4An_6. In a few of the coarser-grained shales and sandstones, it may be seen that this new growth of more basic plagioclase takes place not only as tiny microlites, but also as anorthitic rich rims around primary oligoclase grains. This relationship may be seen more commonly, and easily, in baked sandstones.

Sericite and muscovite are very common in the matrix of most of the shales and mudstones. In many cases, there appears to be a transitional and progressive transformation from sericite, to muscovite, to plagioclase. These minerals are commonly randomly oriented, and it is only in the more strongly metamorphosed rocks that flowage produces semi-parallel orientation. The few relict potash feldspars are typically strongly sericitised. Orthoclase and microcline are rare, but clear, sharp grains of sanidine are relatively common in the coarser-grained parts of the more strongly metamorphosed shales and mudstones. In general, all of the feldspar grains are clear and sharply angular, with the exception of sericitised orthoclase, and fritted grains.

Quartz is abundant, but usually in subordinate amounts to feldspar. Up to five per cent chert is also commonly present. The quartz is clear, unstrained, and angular, but may bear inclusions of magnetite, carbonaceous material, and liquid.

Carbonate may be recognised in most of the shales and mudstones, chiefly in the form of dolomite and siderite. The content of carbonate is usually less than 15 per cent, and typically averages about 10 per cent. A decrease in carbonate content may be noticed in the transformation from sediment to baked product, both in carbonate analyses (Table 5), and in the X-ray diffractograms.

Another mineral which is occasionally recognised in these rocks is cordierite. This mineral is more readily recognised, but is probably less abundant, in baked sandstones. It is easily confused with quartz, but the biaxial figure, alteration characteristics, and yellow pleochroic rim around inclusions help to identify it. X-ray diffractograms also indicate the existence of a magnesium aluminum silicate which closely corresponds to cordierite ($Mg_2Al_4Si_5O_{18}$), in these rocks. This mineral may be formed in these rocks as suggested by Ramberg (1958, p. 61):

$$\underset{\text{low temp.}}{\text{Chlorite} + SiO_2} = \underset{\text{high temp.}}{\text{Cordierite} + \text{Hypersthene} + H_2O}$$

Chlorite is present in small amounts in the original sediments, and may be further developed by the low temperature reaction of muscovite with iron compounds.

Tiny "needles" of a light yellow mineral with very low interference colors, and parallel extinction may rarely be observed in thin section. This mineral is suspected to be melilite (mainly $Ca_2FeSi_2O_7$), and X-ray diffractograms confirm its existance in many of the baked rocks.

Lydon has recently (1964) investigated the occurrence of phosphates in silicate slags from California. Spot tests for phosphates indicate that these compounds also exist in some of the baked rocks and "slags" in the area of study. Very limited testing indicates no predominant mode or area of occurrence. The parent sediments in the area of study typically contain apatite, and this mineral is also present in amounts of one per cent or less in many of metamorphosed rocks. X-ray diffractograms of some baked mudstones also show "peaks" which indicate a mineral closely approaching the formula $AlPO_4$. Other minerals which are found in accessory amounts are zircon, sphene, tridymite, epidote, and garnet.

Slickensiding may also occur occasionally in the baked shales and mudstones (Plate III, Fig. 1). In thin section, this action is seen to produce a "stringing" effect with the hematitic stain, and an elongation of hematite "blebs", both parallel to the slide surface (Plate III, Fig. 3). Other minerals are apparently only slightly effected.

Baked Limestone

Baked limestones are extremely rare in the area of investigation. The most obvious effect of baking on this variety is the production of a fine-grained, heterogranular texture of denticulate sideritic anhedra in an even finer mosaic of carbonate and clay minerals (Plate III, Fig. 8). The limited growth of actinolite, and the lack of diopside and wollastonite, would indicate that the effects of baking have been rather limited. There appears to be a secondary growth of larger (0.1 mm) calcite euhedra, which are unstained by iron compounds. Other minerals which occur in small amounts are quartz, epidote, spinel, sphene, hematite, gypsum, muscovite, plagioclase, and pyroxene.

Baked Sandstone

As a result of the larger grain size, baked sandstones are the best and most easily studied variety of "scoria". In hand specimens, the degree of metamorphism is hard to determine as the sandstones retain their identity until partial fusion occurs. This transition from slightly metamorphosed sandstone to fused rock (Plate IV, Fig. 2) may be very abrupt and the transition zone may often be encompassed in the area of a standard petrographic thin section. This phenomenon makes this variety of "scoria" particularily suitable for study of the mineralogic changes which occur during baking and fusing of the sediments. It is obvious that the macroscopic classification of these rocks as "baked sandstones" actually encompasses metamorphic effects ranging from simple oxidation to partial fusion.

In thin sections, these rocks range in appearance from friable sandstones which are cemented by the oxidation of limonitic material to hematite, to fused rock which contains mainly clear grains of plagioclase and quartz in a matrix of silica glass (lechatelierite) or devitrified silica glass. Cementing materials in the baked rocks may consist of hematite, carbonate, clay minerals, or any combination of these three cementing agents. In the more strongly fused sandstones, cement typically consists of silica glass, or silica glass and hematite. The iron compounds dissolved in the silica glass may sometimes be reduced to magnetite which gives the glass a dark color. Carbonate may also be a secondary cement in some of these partially fused rocks.

The baked sandstones are usually well-sorted, and often cross-bedded. The cross-bedding is frequently emphasized by oxidation of iron compounds to hematite in individual laminations. These laminations generally have a thickness of two millimeters or less. Most of the unmelted mineral grains are sharp and clear. Potassium feldspars are usually the only exception to this generalization.

Quartz is one of the more common minerals, but may be subordinate to plagioclase in the more strongly metamorphosed rocks. Quartz is typically present in amounts of 30 per cent or less, and commonly averages about 25 per cent in many of the less metamorphosed sandstones. It appears as clear, unstrained anhedra, with only slight fritting effecting its periphery, until nearly complete fusion of the rock occurs. Inclusions of magnetite, hematite, and liquid are not uncommon in the strongly metamorphosed quartz grains. Occasionally, tridymite, and very rarely cristobolite, were indicated by X-ray study in some of the nearly fused sandstones. Paramorphs of both of these minerals are relatively common, but the original high temperature form has reverted to more stable, low-temperature quartz. In the partially melted sandstones, quartz is often surrounded by a partially devitrified, clear silica glass. Several thin sections were prepared from an arkosic sandstone which was partially fused in a furnace. X-ray diffractograms and thin section study both showed that tridymite and some cristobolite were present in this specimen (Plate IV, Fig. 8). Apparently these unstable forms of SiO_2 had not yet reverted to more stable quartz.

The ratio between quartz and plagioclase usually decreases in partially fused sandstones. This is caused by the eventual, partial melting of quartz, after plagioclase fusion, and consequent formation of silica glass upon cooling. Plagioclase crystals form during slow cooling over a prolonged liquid-solidus range, while the melted SiO_2 cools rapidly to form silica glass over a higher-temperature, shorter liquid-solidus range. Most of the quartz shows only partial melting, so the maximum temperatures were apparently only slightly above the eutectic melting point for quartz.

Plagioclase is usually present in amounts ranging from 10 to 20 per cent. In the more strongly fused sandstones it may increase to 30 per cent, and be more abundant than quartz. The most common form of plagioclase has a composition of about Ab_7An_3. Probably as a result of rapid cooling, however, compositions transitional between Ab_9An_1 to Ab_3An_7 exist. Rapid cooling may also account for the general lack of good twinning in thin section. In the partially fused sandstones, the original plagioclase is often surrounded by a very thin rim of more calcic plagioclase. This phenomenon may be the reason for the frequently quoted predominance of labradorite in most reports on "scoria". While plagioclase of labradorite composition is present, it is not the dominant plagioclase. An X-ray analysis of several specimens which included the parent sandstone and fused equivalent (collected at location 99, Fig. 3) show several interesting changes. The first is the decreased intensity of the quartz "peak", indicating that some of the quartz has been changed to silica glass. A second, and earlier, change can be seen in the loss of sericite, muscovite, montmorillonite, and carbonate, and the subsequent gain in a more calcic plagioclase. Ramberg (1958, p. 50) has suggested the following equation which may account for this:

$$\underset{\text{epidote}}{2Ca_2Al_3Si_3O_{12}OH} + \underset{\text{muscovite}}{KAl_3Si_3O_{10}(OH)_2} + 2SiO_2$$

$$\rightleftharpoons \underset{\text{anorthite}}{4CaAl_2Si_2O_8} + \underset{\text{orthoclase}}{KAlSi_3O_8} + H_2O$$

While epidote is available in the sediments, it is equally probable that montmorillonite and carbonate may react with sericite-muscovite to form more anorthitic plagioclase. Sanidine is also not uncommon in some of the partially melted sandstones, and may form in place of orthoclase when SiO_2 is in excess.

Several other minerals appear during partial fusion of the sandstone and are apparently related to the plagioclase reaction. These minerals are petalite, cordierite, and the scapolite, melilite. Petalite appears to be limited to sandstones. Cordierite is apparently most common in politic rocks. Melilite occurs as minute needles in fused material and is relatively common in slags. Petalite and melilite are isomorphous mixed crystals, and interchange Ca^{++} and Na^{+} freely with plagioclase. The simplest reaction for this interchange ies

$$\underset{\text{anorthite}}{3CaAl_2Si_2O_8} + CaCO_3 \rightleftharpoons \underset{\text{scapolite}}{Ca_4Al_6Si_6O_{24}(CO_3, SO_4, (OH)_2)}$$

The diffractograms also indicate that limonitic material is oxidized to hematite to form a cementing agent in many of the slightly baked sandstones. With fusion, however, the hematite "peak" is lost, and the hematite is apparently reduced to the ferrous state and dissolved into the glassy matrix. Hematite commonly occurs as disseminated scales which give the sandstones an arkosic appearance.

Silica glass is a major constituent in many of the sandstones, and all of the fused rocks. It increases in amount with increasing fusion, and may be the most common component in some strongly fused sandstones. Indices for this glassy material are reported in the literature to range from about 1.45 to 1.60. The index of glass is dependent on the original composition of fused sediments, and the degree of fusion. Upon initial, partial fusion, a turbid, brownish glass is usually formed which has an index of about 1.55 (Plate IV, Fig. 3). This "glass" is often devitrified, and is composed of minute microlites of untwinned andesine (n greater than Lakeside; equal extinction angles up to 18°), and hematite (?) stain, in a matrix of glass. More complete fusion produces a dark to colorless silica glass. The clear variety of silica glass has an index of about 1.46, and is thought by the writer to be lechatelierite. The darker variety may be colored by magnetite, and has an index of about 1.57.

Gypsum is also a common constituent in many of the baked sandstones. In thin section, it appears as sharp euhedra and as a wavy, fibrous aggregate, with a white or straw yellow interference color.

PLATE IV

BAKED AND MELTED SANDSTONE

Fig. 1.—Baked, columnar sandstone (15, Loc. 15) showing cross-bedding oblique to the columns. Baking effects slight. (One inch reference grid.)

Fig. 2.—Specimen of "scoria" (99a, Loc. 99) showing sharp transition between baked and melted sandstone. The lower part of the specimen is friable, and only slightly altered. (Specimen about seven inches long.)

Fig. 3.—Photomicrograph of a baked sandstone (140a, Loc. 140) showing the initial formation of brown glass "blebs" (cloudy gray grains), surrounded by sericitized plagioclase (mottled gray-white grains), and quartz (clear white grains), in a hematitic-stained, silica glass matrix.

Fig. 4.—Photomicrograph of a baked sandstone (62b, Loc. 62) showing replacement in plagioclase along twin planes by cristobolite (?). Note the sharp, shard-like nature of plagioclase in the upper right corner. Plagioclase grains surrounded by a matrix of hematitic, silica glass (cloudy, dark gray).

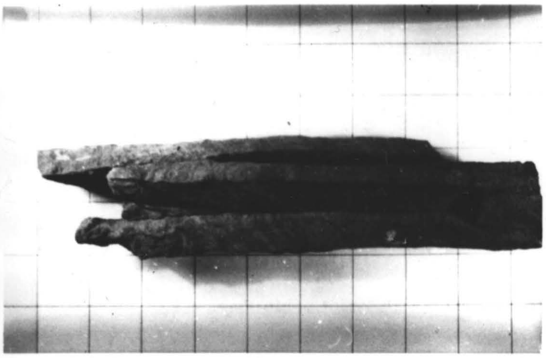
Fig. 5.—Photomicrograph of a baked sandstone (520, Loc. 15) showing almost complete replacement of a plagioclase fragment (center) by carbonate. Surrounding grains of plagioclase are partially dissolved in a silica glass carbonate matrix.

Fig. 6.—Photomicrograph of a baked sandstone (62b, Loc. 62) showing embayed grains of plagioclase (white) melting into hematitic-stained glass (cloudy gray).

Fig. 7.—Photomicrograph of a baked sandstone (140a, Loc. 140) showing a diopside grain (center) surrounded by corroded plagioclase (white) and hematitic glass (dark gray). Note the finely melted border on the plagioclase grain to the right of the diopside grain. Dark, cloudy gray "blebs" are brown, hematitic glass.

Fig. 8.—Photomicrograph of an artificially baked sandstone (402, Loc. 15) showing a cristobolite grain (center) surrounded by webs of hematitic glass (cloudy gray), and grains of plagioclase (white).

All photomicrographs taken with polarizers crossed. Bar scale shows size.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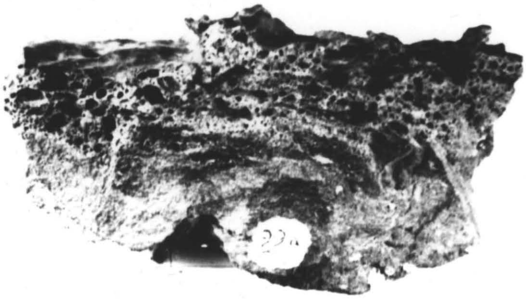
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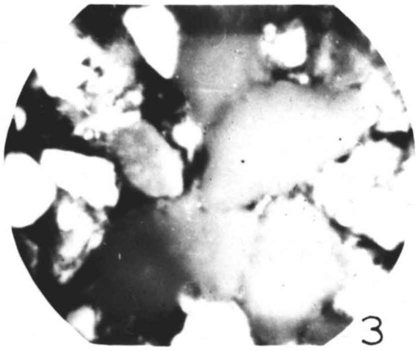
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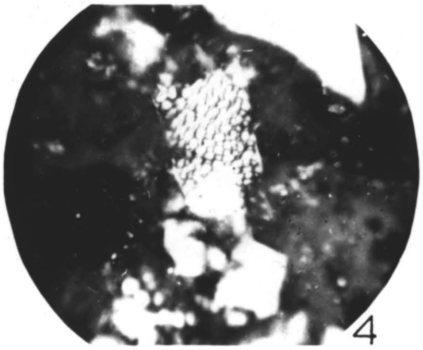
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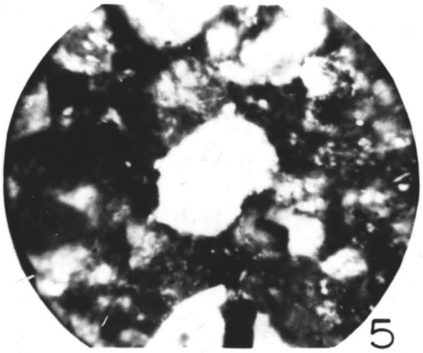
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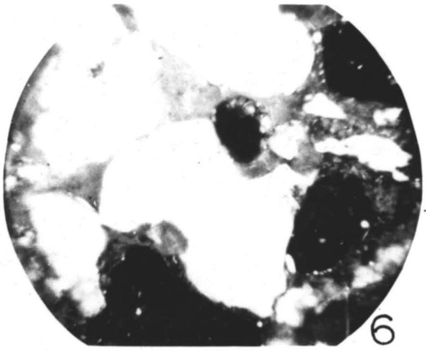
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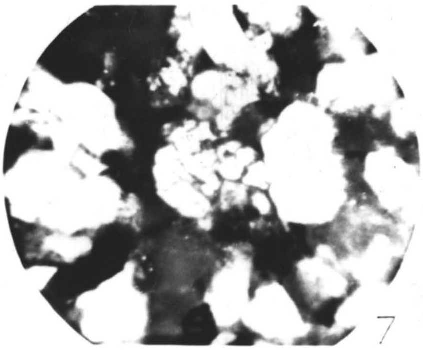
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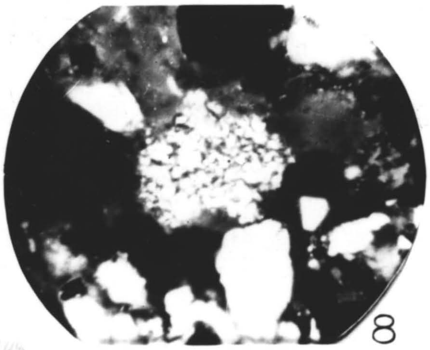
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It is interesting, however, that neither gypsum, hemi-hydrite ($CaSO_4 + \frac{1}{2}H_2O$), nor anhydrite are indicated in diffractograms of the same material. It is probable that the gypsum has been dehydrated beyond the point of hemi-hydration, but not to the point of becoming anhydrite. As such, the resulting compound may become an effective, slow-hydrating cement.

Carbonate appears mainly in the form of calcite and is notable for its replacement of plagioclase (Plate V, Fig. 7). As there are no veins of carbonate, and the replacement has effected only the feldspar fragments, the alteration is thought to be deuteric. Carbonate content ranges from two to 15 per cent, and averages about six per cent for most of the sandstones. Siderite appears to be the second most common carbonate.

Sericite-muscovite is a common, but never very abundant constituent in the baked sandstones. It is most common in those rocks which contain up to 10 per cent potassium feldspar. Potassium feldspar, with the exception of sanidine, is usually rare in any type of "scoria". When it does occur, it is almost always more or less replaced by sericite. In the sandstones, grains of orthoclase are commonly preserved only as relicts, and the replacing sericite may be transitional in alteration to muscovite.

Mafic minerals are relatively rare in baked sandstones. This is not surprising considering the paucity of these minerals in the parent sediments. Biotite relicts are not uncommon, however, and are usually transitional to limonitic material or hematite. In the more calcareous sandstones, the mafic minerals actinolite, tremolite, and diopside become more abundant with increasing metamorphism. Diopside is the

PLATE V

PHOTOMICROGRAPHS OF BAKED "SCORIA"

Fig. 1.—Baked limestone (32b, Loc. 32) showing texture, and a few small grains of actinolite (dark grains). Mixed carbonate (mainly siderite), and clay mineral matrix.

Fig. 2.—Partially melted sandstone (19j, Loc. 19) showing quartz (white, irregular) and plagioclase (white, shard-like) fragments floating in a matrix of silica glass, carbonate, and hematitic glass.

Fig. 3.—Baked sandstone (15x, Loc. 15) showing a quartz grain (center) with a melted, silica glass rim bordered by hematitic-stained glass. Small relicts of plagioclase remain in the silica-glass.

Fig. 4.—Artificially fused sandstone (130b, Loc. 15) showing a cristobalite grain (upper center), plagioclase (sharp, white grains), and mullite needles in a matrix of silica glass.

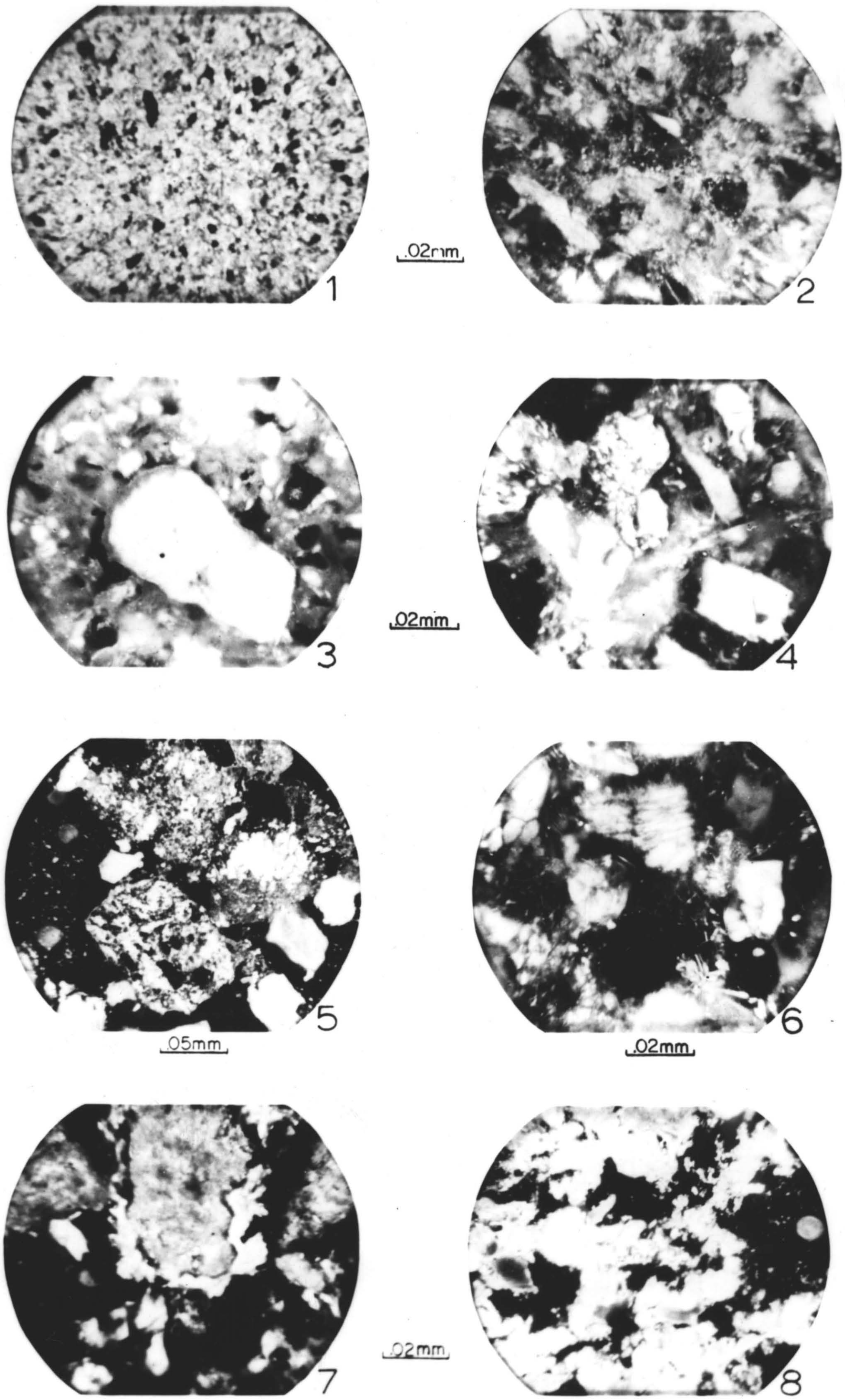
Fig. 5.—Baked sandstone (106, Loc. 106) with cristobalite and tridymite paramorphs surrounded by smaller grains of plagioclase (white) in a clear, silica glass matrix.

Fig. 6.—Artificially fused sandstone (400, Loc. 15) showing a gypsum fragment (upper center), diopside grain (lower left), and tiny microlites of melilite in a calcareous-glassy matrix. Note vesicles, and melted borders on plagioclase.

Fig. 7.—Baked sandstone (19, Loc. 19) showing the growth of calcite from the border of a sericitized grain of plagioclase. Quartz grains (lower left) show partial melting. Clear silica glass-calcareous matrix.

Fig. 8.—Baked and melted sandstone (15a, Loc. 15) showing tridymite paramorphs in a clear, glassy matrix.

All photomicrographs taken with crossed polarizers. Bar scale shows size.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commonest of the three, and typically occurs as a light green, slightly pleochroic, often twinned, subhedral crystal with a biaxial positive figure, and an extinction angle of about -39° in sections parallel to the c-axis. Actinolite-tremolite is relatively rare, and typically occurs as long prismatic crystals in fibrous aggregates. There is a gradation between the green actinolite and a clear mineral having similar optical characteristics and it is assumed that the clear variety is tremolite. All three minerals appear to bear transitional relationships to one another. It is likely that actinolite-tremolite is produced by the reaction of calcite and other carbonates with montmorillonite to form actinolite and epidote at higher temperatures. At still higher temperatures it is probable that diopside is produced by the following reaction (Ramberg, 1958, p. 63):

$$3CaCO_3 + \underbrace{Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2}_{\text{actinolite}} + 2SiO_2 \underset{\text{high temp.}}{\overset{\text{low temp.}}{\rightleftharpoons}} \underbrace{5Ca(Mg, Fe)Si_2O_6}_{\text{diopside}} + 3CO_2 + H_2O$$

These mafic minerals have also been confirmed by X-ray analysis. Other mafic minerals which occur rarely are hypersthene, epidote, and fayalite.

Magnetite occurs in amounts which range up to several per cent in the more strongly fused sandstones. An iron sulfate has also been indicated in some of the sandstones when studied by X-ray diffraction analysis. Jarosite appears mainly in the carbonate and hematite rich sandstones and may be the iron sulfate indicated in X-ray diffractograms.

Other accessory minerals which occur in many of the baked sandstones are zircon, sphene, apatite, rutile, corundum, mullite, and jarosite. Zircon and apatite are ubiquitous. Sphene, corundum, and mullite occur rarely, in small amounts, in the partially fused sandstones. Rutile is a very rare mineral which occurs as needle-like intergrowths in quartz.

Porcellanite

Porcellanite is a distinctive variety of "scoria". It is a compact, hard, pastel-colored, aphanitic rock with the texture and fracture of unglazed porcelain (Plate III, Fig. 2). The colors of this variety have almost as wide a range as the baked rocks discussed previously, but the colors are typically more pastel in hue. The predominant colors are light pinks, yellows, buff, pastel greens, and lavender. A semi-conchoidal fracture is typical on the broken surface of these rocks. In thin section, the most striking characteristic is the uniform, very fine grain of clay-size particles (Plate III, Fig. 4). A very few grains may attain a size of 0.05 mm, but the average grain size is in the magnitude of 0.005 mm. The rare, larger particles indicate that porcellanite is composed of very fine-grained fragments of plagioclase, gypsum, and quartz in a cryptocrystalline matrix of these same minerals, plus micaceous minerals, carbonates, clay minerals, hematite, and silica glass. The hardness of porcellanite is probably the result of the estimated 10 to 15 per cent content of silica glass. The carbonate content averages a rather uniform 15 per cent which may be significant as a proper proportion for uniform fluxing. X-ray diffraction studies confirm the existence of the previously mentioned minerals, and indicate that the carbonate is calcite.

Mottling of these rocks is a common characteristic and the line of color change may be hair-line sharp (Plate III, Fig. 2). Mottling may be the result of variation in temperature, or content of iron compounds in some cases, but it is believed by the writer that these very sharp demarcations are usually caused by the effects of interstitial migration of gases.

<u>Vitrified Siltstone</u>

Vitrified siltstone is a fairly common variety of "scoria" that occurs near the base of a strongly metamorphosed "scoria" outcrop or near "chimney" zones. It has a typical scoriaceous appearance. Vitrified siltstone is usually transitional to glassy slag, and hand specimens may have a melted surface which resembles ropy lava (Plate VI, Fig. 1). Broken specimens usually show a rough, finely-vesicular texture. The uniform, finely-vesicular nature would indicate that the heat was barely great enough to bring about nearly complete fusion and de-volitilization, and that the melted material was still relatively viscous. As a result of vesicularity, some of the vitrified siltstone has a bulk specific gravity approaching one (Plate VI, Fig. 3).

On the other hand, the vitrified siltstones are transitional to baked rocks, and show approximately the same mineralogy. In degree of metamorphism the rock approaches that of the most strongly metamorphosed, baked sandstones. The most obvious changes from the baked rocks are increased vesicularity, increased content of a strongly-hematitic stained, glassy matrix, re-crystallization of more calcic plagioclase, and partial melting of quartz. In many specimens, the larger grains of quartz can be seen to be embayed and surrounded by a

PLATE VI

VITRIFIED SILTSTONE AND VITRIFIED LAMINATED SHALE

Fig. 1.—Vitrified siltstone (Loc. 15) showing the characteristic ropy melted surface, and extreme vesicularity. (One inch reference grid.)

Fig. 2.—Vitrified laminated shale (37b, Loc. 37) showing marked lamination. (One inch reference grid.)

Fig. 3.—Photomicrograph of a vitrified siltstone (55p, Loc. 55) showing extremely fine vesicularity of the silica glass matrix. (Plain polarized light.)

Fig. 4.—Photomicrograph of a vitrified laminated shale (40c, Loc. 40) showing a glassy lamination with aligned microlites of feldspar and sericite. Surrounding laminations (light-colored) composed of a matrix of clay minerals, plagioclase (small white grains), and hematitic silica glass. (Crossed polarizers.)

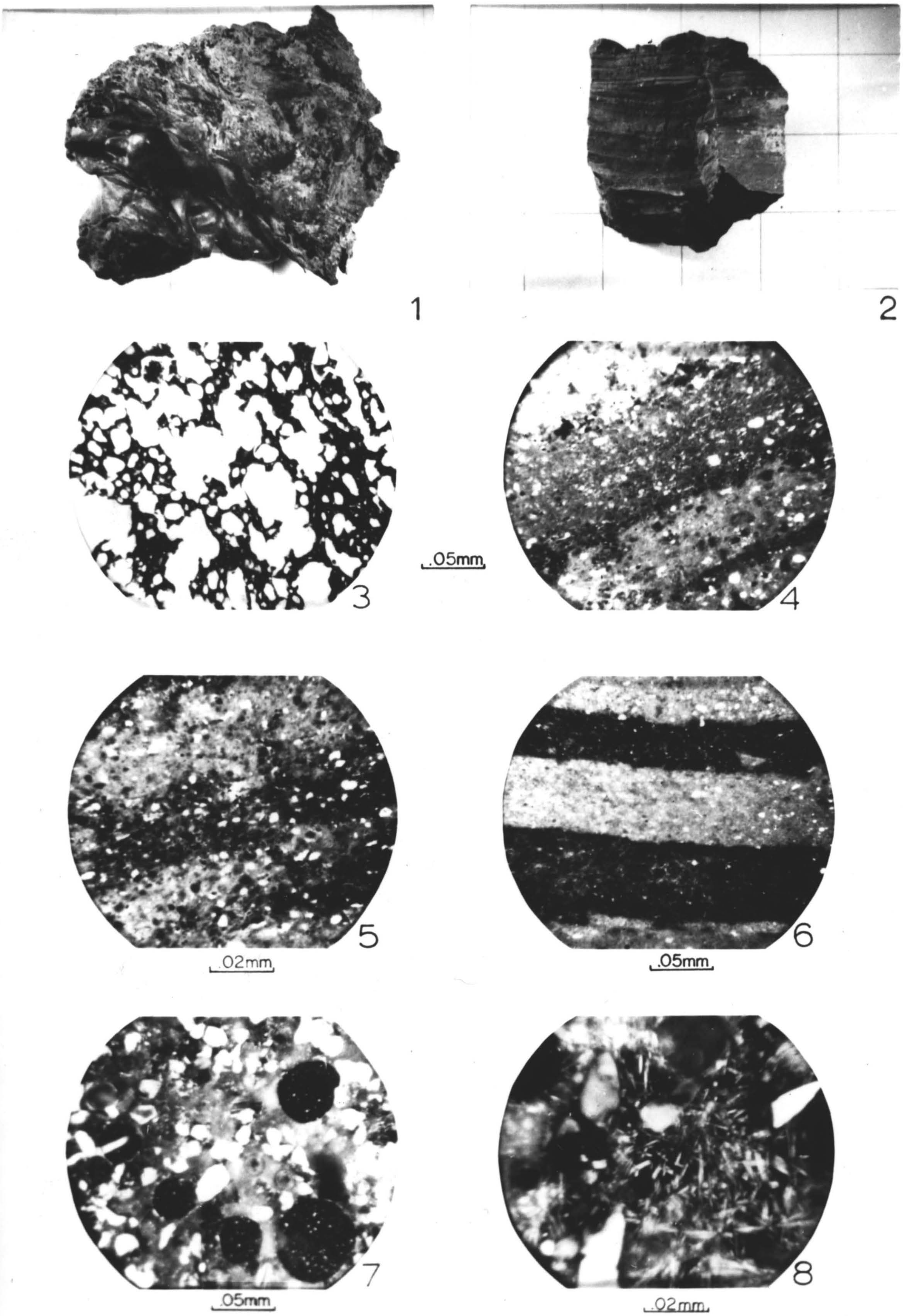
Fig. 5.—Photomicrograph of a vitrified laminated shale (34a, Loc. 34) showing a glassy lamination and magnetite, pyrite, and plagioclase inclusions in a clay mineral-silica glass matrix. (Crossed polarizers.)

Fig. 6.—Photomicrograph of a vitrified laminated shale (37c, Loc. 37) showing the sharp demarcation between the dark glassy laminations and the hematitic-stained, clay mineral matrix. Dark colored, glassy laminations contain magnetite and pyrite inclusions. (Crossed polarizers.)

Fig. 7.—Photomicrograph of a vitrified siltstone (130a, Loc. 130) showing vesicles developed in silica glass. Large white grains are plagioclase. Matrix of silica glass (cloudy grey), partially dissolved plagioclase, and quartz. (Crossed polarizers.)

Fig. 8.—Photomicrograph of a very coarse, vitrified siltstone (130b, Loc. 130) showing the development of mullite and melilite microlites. Brown, glassy "blebs" (mottled grey) and sharp grains of plagioclase (white) surround the microlites. Matrix composed of silica glass. (Crossed polarizers.)

Bar scale shows size.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thin rim of silica glass. In the same specimens, shards of newly formed plagioclase, and microlites of plagioclase attached to feldspar grains, are formed. The melted material would therefore have become enriched in SiO_2, which would account for the increased amount of silica glass. It is probable that the selective melting of the albitic fraction of plagioclase, upon initial vitrification, would result in marginal enrichment of anorthite around plagioclase grains. The establishment of anorthite-rich rims would prohibit the further melting of plagioclase, until temperatures were raised considerably, and the anorthite-rich rims account for the bi-modality of plagioclase which is indicated by optical and X-ray diffraction studies. This would also suggest that the melt is first enriched in soda, but with increased fusion, both soda and lime are decreased in the glassy material. Cordierite is often a common constituent in some of the vitrified siltstones.

Vitrified Laminated Shale

These rocks are typically located in "chimney" zones. They usually have a dull external appearance, and are irregularly banded in various shades of red and green or black (Plate VI, Fig. 2). The exposed surface may take on a high polish with weathering. Thin sections cut across the laminae reveal the presence of strong hematitic staining in the red areas and magnetite and carbon in clear to dark glass in the green or black areas (Plate VI, Figs. 4 and 6).

Ordinarily the grain is so fine, and hematite-stained, that little can be observed under the microscope. The texture is similar to that observed in porcellanite, but these laminated rocks apparently contain more iron, as indicated by their darker colors, and by hematite-staining. The bands of color are caused by selective melting along specific laminae which result in the formation of stained, glassy material. These laminae are composed of a clear to dark, slightly recrystallized, isotropic glass, having an index of about 1.46. The silica glass appears to be lechatelierite (SiO_2), and it includes very tiny semi-oriented laths of plagioclase (?) and crystals of magnetite. Some of the darker glass also appears to contain carbon particles. The orientation of the microlites, semi-parallel to the laminae, indicate that flowage has taken place (Plate VI, Fig. 4). When cut, the dark glassy bands have a dull, gray-black, metallic luster.

This variety of "scoria" generally has a very low carbonate content (0 to 3 per cent). It is suspected that the location of the melted laminae may be determined by concentration of carbonate in these bands, which provided a fluxing effect, and consequent selective fusion.

Only a few larger grains of plagioclase, muscovite, and occasional biotite, quartz, and magnetite can be identified under the microscope. Hematite stains most of the glassy material throughout the slide, with the exception of the clear to dark, gray-brown, glassy laminae.

X-ray diffraction studies, however, indicate that the mineralogy is more complex. Besides the minerals previously mentioned, it appears that actinolite-tremolite, cordierite, and tridymite are usually present. Plagioclase ranging from calcic albite to sodic labradorite is present, but andesine is the most common plagioclase composition. Some sanidine may also be present. Other minerals which occur in some of the specimens in small amounts are diopside, melilite, mullite, and sphene. Natrojarosite, a hydrated magnesium aluminum silicate (cordierite ?), and petalite (?) are also rarely indicated in a few specimens.

<u>Glassy Slag</u>

Specimens of glassy slag large enough to be observable in hand specimens occur just above the burning lignite, along the fractures which served as vents in "chimneys", and in small cracks leading away from these areas. Most of the glassy slag is concentrated near the top of the "chimneys" where the inrush of air apparently rapidly cooled the melted material, after the initial explosive reaction of entrapped gases. It is also probable, as suggested by Rogers (1918, p. 6), that partial collapse of the "chimneys" forced some of the molten material into crevices of the resulting brecciated mass, where it cooled rapidly. Most of the glassy slag is highly vesicular, and more or less devitrified. Even where devitrification is complete, however, the microlites are usually of such small size that their mineralogy cannot be determined by optical means. A very small amount of the material is an actual glass, which is dense and dark, and resembles obsidian.

Some of the highly vesicular material has a bulk specific gravity less than one. It is this variety which mimics true scoria perfectly. The glassy material varies considerably with respect to index of refraction, specific gravity, and degree of devitrification, even within an individual specimen. The index of refraction varied between 1.51 to 1.55, with the most common index being about 1.53. Specific gravity of the ground material varied from 2.57 to 2.71. The presence of some magnetite in the glass makes it slightly to moderately magnetic, and probably accounts for some variation in specific gravity (Plate VII, Figs. 4 and 5).

In thin section, the glasses range in color from light gray to black, but dark hematitic reds predominate. The black and dark gray colors result from concentrations of euhedral magnetite (Plate VII, Fig. 5). In some of the more coarsely devitrified patches, tiny, square to rectangular crystals appear to indicate the formation of plagioclase. Certain irregular brownish areas apparently represent portions of glass in which the incipient crystallization of pyroxene has commenced. Vesicles range from about 1 mm to 0.15 mm, and are usually the site of initial devitrification. Hematite is usually concentrated around the vesicles, and along cracks in the glass.

X-ray diffraction investigation indicates the extreme complexity of the mineralogy, which is a reflection of the disordered state of a mixture of partly crystallized minerals. Magnetite, the pyroxenes, clinoenstatite, diopside, and hypersthene, or the amphiboles, actinolite-tremolite are invariably present in all of the glasses. It appears that the pyroxenes form first, depending on the amount of calcium and iron present, and that actinolite-tremolite forms somewhat later. Diopside and actinolite-tremolite typically occur in association with more silic silica glasses. The relationship between these minerals is represented by the following reaction (Ramberg, 1958, p. 150):

$$2SiO_2 + 3CaCO_3 + \underset{\text{tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} \underset{\text{higher temp.}}{\overset{\text{lower temp.}}{\rightleftharpoons}} \underset{\text{diopside}}{5CaMgSi_2O_6} + 3CO_2 + H_2O$$

PLATE VII

GLASSY SLAG AND RECRYSTALLIZED SLAG

Fig. 1.—Glassy slag (53c, Loc. 53) showing brecciation which is common in this variety of "scoria". (One inch reference grid.)

Fig. 2.—Glassy slag (99c, Loc. 99) showing the glassy surface, and vesicularity of this variety. (One inch reference grid.)

Fig. 3.—Photomicrograph of a recrystallized slag (222, Loc. 130) showing calcite partially filling a vesicle (upper left). Recrystallized matrix is composed of diopside (laths), plagioclase (white grains), and calcite with some hematitic, devitrified glass (cloudy, gray). (Crossed polarizers.)

Fig. 4.—Photomicrograph of the same recrystallized slag (222, Loc. 130) showing crystals of diopside and clinoenstatite (large, white grains) in a matrix of plagioclase, magnetite (small, black crystals), and devitrified silica glass. (Crossed polarizers).

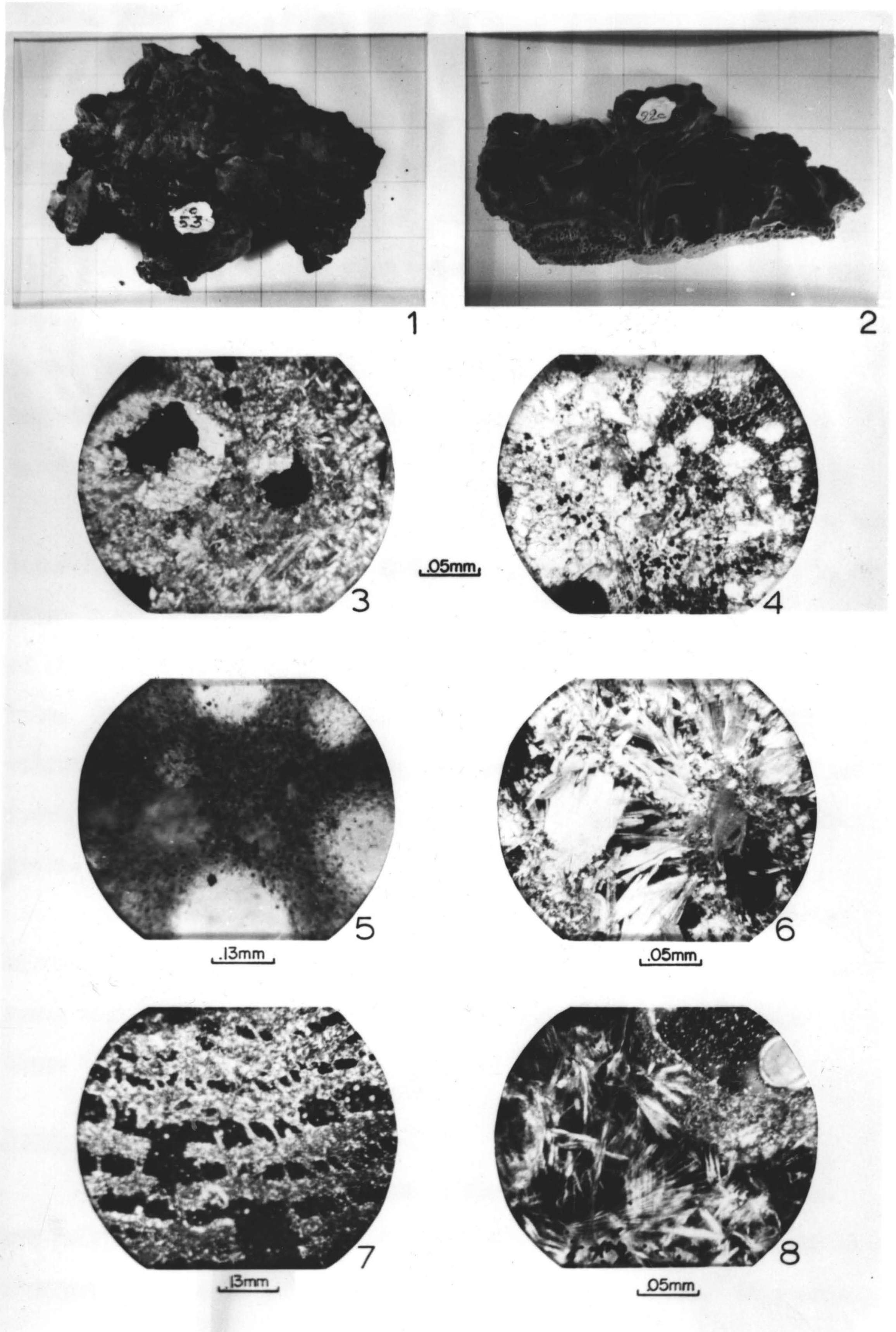
Fig. 5.—Photomicrograph of a glassy slag (B, Loc. 130) showing a concentration of euhedral magnetite in devitrified glassy matrix. Note the vesicles (white). (Plain polarized light.)

Fig. 6.—Photomicrograph of a recrystallized slag (401, sec. 28, T. 140 N., R. 101 W.) showing recrystallization of large crystals of diopside, and fibrous actinolite-tremolite in a devitrified silica glass-plagioclase matrix. (Crossed polarizers.)

Fig. 7.—Photomicrograph of woody cell structure preserved in recrystallized slag (401, sec. 28, T. 140 N., R. 101 W.). Woody structure replaced by devitrified silica glass. (Crossed polarizers.)

Fig. 8.—Photomicrograph of a recrystallized slag (401, sec. 28, T. 140 N., R. 101 W.) showing needle-like crystals of actinolite recrystallizing from a completely devitrified glassy matrix. (Crossed polarizers.)

Bar scale shows size.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Little, if any, hematite was indicated in any of the glassy slags. It is probable that hematite is directly reduced to ferrous iron compounds, and that it may also react with actinolite to form magnetite as shown below (Ramberg, 1952, p. 144):

$$5Fe_2O_3 + 2CO_2 + Ca_2Fe_5Si_8O_{22}(OH)_2 \rightleftharpoons 2CaCO_3 + 5Fe_3O_4 + 8SiO_2 + H_2O$$

Plagioclase was indicated optically only in those specimens which showed distinct signs of rather complete devitrification in thin section. In these specimens, the typical plagioclase was oligoclase, but andesine was also identified in association with oligoclase in two specimens.

A magnesium aluminum silicate was indicated in all specimens, but the diffractogram "peaks" did not correspond exactly to cordierite, or other listed minerals. Other minerals which occur occasionally in some of the specimens are forsterite, petalite, iron chamosite, and melilite. It is also suspected that an intermediate type of scapolite exists in some of the specimens. Quartz is not present in any of the specimens and is apparently in a completely amorphous state as silica glass.

A number of "peaks" could not be correlated with any specific mineral, but the range of placement on different diffractograms suggests that a mixture of two end member scapolites may account for these "peaks".

<u>Recrystallized Slag</u>

Glassy slags which have cooled slowly enough to recrystallize are relatively rare, but are of considerable petrographic interest as they provide insight into high temperature modifications. This mate-

Table 6.--Estimated mineral content of selected fine-grained varieties of "scoria"

Specimen No. and Location	"Scoria" Variety	Munsell Color Number	% Quartz	% Tridymite	Ab9	% Plagioclase	Ab3
15a, Loc. 15, (Fig.3)	B. Mudstone	5R5/4	15			5	
32a, Loc. 32, (Fig.3)	B. Limestone	N5					
40f, Loc. 40, (Fig.3)	B. Mudstone	10R6/6	20	5		10	
40g, Loc. 40, (Fig.3)	B. Mudstone	10R5.5/5	20			15	
55f, Loc. 55, (Fig.3)	B. Mudstone	10R6/6	20			10	
89d, Loc. 89, (Fig.3)	B. Mudstone	10R6/6	15			20	
66a, Loc. 66, (Fig.3)	Porcellanite	10R5/6	20			10	
66e, Loc. 66, (Fig.3)	Porcellanite	5YR7.5/4	5			5	
77a, Loc. 77, (Fig.3)	Porcellanite	5YR7/4					
34a, Loc. 34, (Fig.3)	Vit. Lam. Sh.	Variable				15	
37b, Loc. 37, (Fig.3)	Vit. Lam. Sh.	Variable	5			10	
40c, Loc. 40, (Fig.3)	Vit. Lam. Sh.	10R5/5	15	5	5		
X, Loc. unknown	Vit. Mudstone	10R3.5/5	20	T		30	
40b, Loc. 40, (Fig.3)	Glassy Slag	Variable					
55k, Loc. 55, (Fig.3)	Glassy Slag	10R5/6				3	
71a, Loc. 71, (Fig.3)	Glassy Slag	N4/5	2			5	
B, Loc. 130, (Fig.4)	Glassy Slag	10R4/6					
R, Loc. 130, (Fig.4)	Glassy Slag	10R3/2.5				10	

Table 6.—Continued

% K-Feldspar	% Hydromica	% Clay Minerals	% Limonitic Mat. % Hematitic Mat.	% Calcite[a]	% Dolomite % Siderite	% Biotite	% Melilite	% Glassy Mat.	Cement	Remarks
	5						10		60% Hema-clay-carb.-glass	
		20	10		58				Siderite	
	20		30	1		2		10	Hematitic glass	Trace zircon
	5	10	20		1			29	Glass-hematite	T. zircon, & sphene
	5	20	15		14	1		15	Hema-glass-clay-carbonate	T. zircon semi-porcel.
5	15		20		12		T		Clay-hematite	
	10			10	5	T			40% Hematitic glass-carbonate	Molted plagio.
	5	40	13		12				20% Hematitic glass-carbonate	
		60	5	20				5	Clay mineral-glass	
	5							25	45% Hematitic-glass	10% mag., T. carbonaceous
	5		20					50	Hematitic glass	10% magnetite
T			30					30	Hematitic glass	10% diopside, 5% magnetite
	10		15					25	Hematitic glass	T. epidote
	5		10					80	Hematitic glass	5% magnetite
			12	2				80	Hematitic glass	3% magnetite
							2	85	Silica glass	5% mag., T. zircon
			15					80	Hematitic glass	5% magnetite
	5		13					70	Hematitic glass	2% magnetite

[a]Volumetric analysis

rial is probably confined to the lower part of the "chimneys", where high, but gradually decreasing temperatures were maintained for a considerable time. In hand specimen, the appearance of recrystallized slag is much the same as that of glassy slag, and cannot be differentiated from it. The conditions necessary for formation of this type of slag are apparently quite rare as only four of some thirty glassy slags showed significant recrystallization. All gradations between devitrified glass and holocrystalline material may be encountered, even in one thin section. Crystals range in size from tiny microlites up to needles or laths 2 mm in length. Even the most completely recrystallized specimens contained interstitial glass. The least recrystallized specimens consist of amorphous silica glass with a few centers from which acicular crystals radiate. It appears that mullite and melilite are the first crystals to form, followed by diopside, if recrystallization takes place directly from a melt. If the glass is devitrified, plagioclase may crystallize penecontemporaneously with these minerals, otherwise it apparently appears somewhat later. It is probable that sphene, zircon, magnetite and olivene crystallize earlier, but with the exception of magnetite, these minerals are only rarely recognized. Most of the rocks are vesicular and the vesicles are favored loci for initiation of crystalization and the concentration of iron oxides, particularily hematite. Strongly hematitic-stained crystals often radiate from the periphery of the vesicles (Plate VII, Fig. 6). Vesicles are occasionally filled or partially filled by clear or fibrous calcite and a zeolite (?) (Plate VII, Fig. 3). The minerals actinolite-tremolite appear somewhat later than diopside and they are apparently the more stable low temperature assemblage.

One of the better recrystallized specimens (No. 222), collected at location 130 (Fig. 4), shows many of the characteristics common to recrystallized slags. Two distinctly different areas can be distinguished in thin section. A light greenish-gray area is dominated by an assemblage of plagioclase, sanidine, actinolite-tremolite, silica glass, melilite, mullite (?), and cristobalite. The darker, red to black area contains a dominant assemblage of hematite, magnetite, diopside, carbon particles, and clinoenstatite. The most common plagioclase appears to have a composition between andesine and labradorite. The microlites of plagioclase have a maximum extinction angle of about 32°. All of the plagioclase is untwinned. Sanidine is only rarely determined by low indices, small 2V, and a biaxial negative figure. Melilite occurs as light yellow, tabular euhedra with weak birefringence, and high relief. Diopside is present as light green prismatic euhedra with a biaxial positive figure, 2V = 60°, and maximum extinction angle of about -38° to the c-axis. It is distinguished from actinolite-tremolite by the larger extinction, and crystal habit.

X-ray diffraction investigation confirmed the presence of the optically determined minerals and indicated the further existence of cordierite, mullite, cristobalite, enstatite, fayalite, kyanite (?), and a scapolite (?). There is no indication of quartz, but a small amount of cristobalite is present. Apparently the SiO_2 is taken up in the other minerals, and is present partially as amorphous silica glass.

Several large pyroxene crystals in this thin section are composed of minute scales of the same pyroxene, which is suspected to be enstatite, as indicated by X-ray diffraction. The crystals have a schiller structure and may be the ferroan variety of enstatite known as townite. Many of the diopside crystals appear to be altering to actinolite-tremolite.

Two other specimens (No. 401 and 404), collected in sec. 28, T. 140 N., R. 101 W. (Fig. 2), showed a less complex mineralogy. Both specimens were composed of a dark colored glass which had recrystallized largely to cordierite, actinolite-tremolite, diopside, and magnetite. X-ray diffraction investigation showed the existence of tridymite, and iron sanidine in specimen No. 401, and another magnesium aluminum silicate in specimen No. 404. The former specimen is one of the few in which tridymite is abundant.

A fourth specimen, No. 19 (Loc. 19) also has a less complex mineralogy, being composed mainly of labradorite-bytownite, silica glass, enstatite, magnetite, mullite, and small amounts of melilite and cristobalite. This specimen contained the most calcic plagioclase (bytownite) of all the recrystallized slags.

The occurrence of calcite and other carbonates in vesicles of all of these recrystallized slags might be explained as secondary deposition, but the appearance of these same carbonates in the matrix of the slags makes this explanation unlikely. It is more likely that these carbonates are formed by the reaction of carbon dioxide with actinolite (Ramberg, 1958, p. 144).

$$7CO_2 + Ca_2Fe_5Si_8O_{22}(OH)_2 \rightleftharpoons 2CaCO_3 + 5FeCO_3 + H_2O + 8SiO_2$$

Other accessory minerals which appeared in most of the recrystallized slags are garnet, zircon, sphene, epidote, spinel, and biotite relicts. Although garnet might be expected, particularily in metamorphosed pelitic rocks, the mineral is usually rare. Carbonate typically retards the formation of this mineral, and higher pressures are more favorable for its formation. Thus, garnet would not be expected to form in the relatively high-carbonate, low-pressure milieu common to the formation of "scoria".

Other minerals which might be expected to form are wollastonite, staurolite, kyanite, sillimanite, and corundum. Only one specimen (No. 40b) showed indication of extensive formation of wollastonite. It is probable that the parent sediment was a silty limestone. The lack of SiO_2 and other minerals suggest that wollastonite formed by the following reaction (Ramberg, 1958, p. 155):

$$\underset{\text{calcite}}{CaCO_3} + SiO_2 \rightleftharpoons \underset{\text{wollastonite}}{CaSiO_3} + CO_2$$

Staurolite was never identified in any of the specimens, and kyanite was indicated only rarely by X-ray diffraction. The optical and X-ray characteristics of sillimanite and mullite are so similar that these could not be distinguished from one another. As mullite is the more stable mineral, and is particularily common in furnace slags, the minerals which had characteristics common to sillimanite-mullite were arbitrarily identified as mullite.

The occurrence of mullite (or sillimanite), and the lack of corundum is particularily significant in the estimation of maximum temperatures of "scoria" formation. Mullite, unlike most of the other minerals encountered in "scoria", is extremely refractory, and its eutectic is less effected by polycomponent systems, than is that of most other minerals. If the melt could be considered a simple two component system composed of about 60 per cent silica and 40 per cent alumina, mullite would begin to form at about 1,800°C. The association of cristobalite and mullite would begin to crystallize at about 1,500°C,

Table 7.--Point count analysis of selected coarse-grained varieties of "scoria"

Specimen No. and Location (Fig.)	"Scoria" Variety	Munsell Color Number	% Quartz	% Tridymite	Ab9	% Plagioclase	Ab3	% K-Feldspar	% Hydromica	% Biotite	% Clay Minerals
12a, Loc. 12 (3)	B. Sandstone	10R5.5/4.5	18			13		T			3
15c, Loc. 15 (3)	B. Sandstone	5YR6/4.5	32		12	2		1	T	T	16
19j, Loc. 19 (3)	B. Sandstone	10YR5.5/4	32		14	5		5	T	T	8
54a, Loc. 54 (3)	B. Sandstone	10R5.5/5.5	25		9	1		6	T	T	3
87b, Loc. 87 (3)	B. Sandstone	10R5.5/5.5	19	T	9	2		1	T	1	
87c, Loc. 87 (3)	B. Col. Ss.	10R5.5/5	22			11		3		T	
106a, Loc. 106 (4)	B. Sandstone	10R5.5/5	42	T	8	2		4		T	1
110a, Loc. 110 (4)	B. Sandstone	N5	28		7	7		5	1		
130b, Loc. 130 (4)	Syn. B. Ss.	5Y5/1	17				18		T		
312, Loc. 15 (3)	B. Col. Ss.	10R5/6	28		4	8		1	1		
360, sec. 33, T. 141 N., R. 101 W.	B. Col. Ss.	5YR5.5/5	27		6	10		1	4	T	
402, Loc. 15 (3)	Syn. B. Ss.	10R5.5/5.5	37	T	7	12		2	1	1	3
490, Loc. 15 (3)	B. Sandstone	10R5.5/3	30	T	5	12		1	2	T	T
19g, Loc. 19 (3)	Rexled. Slag	N3	15				10			T	20
40i, Loc. 40 (3)	Rexled. Slag	N6									
40l, Loc. 40 (3)	Rexled. Slag	Variable		5			T				
222, Loc. 130 (4)	Rexled. Slag	N3		T			25				

Table 7.--Continued

% Calcite[a]	% Limonitic Mat.	% Hematitic Mat.	% Actinolite	% Tremolite	% Diopside	% Mellilite	% Glassy Mat.	% Unidentified	Cement	Remarks
8		30					20	8	Hematitic glass	Calcite repl. plagio., T. mag., sericite.
9		7					7	4	Hema.-glass-carbonate	2% gyp., T. cordierite.
4		13					10	9	Hematitic	T. gypsum, epidote, & sericitized feldspar.
14		12					18	12	Hema.-glass-carbonate	T. epidote. Sericitization of feldspar.
		21					43	5	Hematitic glass	T. sanidine, microcline. Bio. alt. to limonite.
2		30					32	0	Hematitic glass	T. sanidine, microcline, rutile. Bio. alt. hema.
5		11		T			27	0	Hematitic glass	Trace gypsum, magnetite, rutile, epidote, sid.
15		14					19	4	Hematitic glass	T. mag., siderite. Bio. alt. to limo-hematite.
					2	15	33	0	Silica glass	10% gyp., 5% mag. T. zir., mullite, epidote.
	6	25					24	3	Hematitic glass	Trace microcline.
12		16		T			17	5	Hematitic glass	2% cordierite, T. micro, epidote, siderite.
T		11	1		T		25	0	Hematitic glass	Trace epidote, zircon, siderite.
16	15				T		17	0	Hematitic	2% cordierite. T. micro, hypersthene.
	10					T	30		Devitrified silica glass	10% carbonaceous. 5% mag. T. epidote, mullite.
		T	5		2		95	3	Devitrified silica glass	Cordierite, natrojarosite. Vesicular.
0			30		40		20	5	Devitrified silica glass	Cordierite, Fe sanidine. Vesicular.
5		5		T	20		30	5	Devitrified silica glass	5% augite, 5% magnetite. T. cristobolite, mullite, fayalite, carbonaceous, sanidine, cordierite.

[a]Volumetric analysis

and would end at about 1,470°C. The lack of corundum may indicate either that its crystallization temperature (1,825°C) was never attained, or that the melt was undersaturated in Al_2O_3. Complete reversion to mullite is unlikely because of the rapidity of cooling. As the association of cristobolite and mullite has been observed, it would appear that maximum temperatures were greater than 1,470°C, and less than 1,825°C.

The association of cordierite and tridymite in the three component system $MgO-Al_2O_3-SiO_2$ would also indicate a minimum formational temperature of about 1,350°C (McNamara, 1945, p. 298-314).

Summary of Classification

Use of the term, "Scoria"

These baked and melted sediments, locally referred to as scoria or clinker, have borne a long list of synonyms, both in the United States and in Europe. The plethora of names, in itself, indicates the unsatisfactory state of classification for this metamorphic rock type. In the United States the names scoria, clinker, porcellanite, clinker-till, natural brick, pseudo-scoria, "silicate slag", natural slag, pumice stone, pumiciform stone, baked shale, and psuedo-igneous rock have been used for this metamorphic rock, or varieties of it. In Europe, the terms gebrannter ton, kohlenbrandgesteine, porzellanit, and porzellanjaspis have been used for similar material. With the possible exception of "silicate slag", natural slag, baked shale, psuedo-igneous rock, gebrannter ton, and porzellanjaspis, these names have been used to describe the complete suite of metamorphosed rocks herein described under the name "scoria".

Clinker, the term recently favored by many geologists in North Dakota, was apparently first suggested by Prince Maximilian on his return from North Dakota in 1833. He, and other subsequent authors, commented on the sound of "scoria" being when struck, "like that of the best Dutch clinkers", and it is apparently this clinking sound, rather than the resemblance to the furnace product, from which the term, "clinker", was coined. Unfortunately, however, this name does suggest a resemblance to furnace clinker, which does not adequately describe all varieties of "scoria". In common with "scoria", the term, "clinker", is also open to criticism from a petrographic standpoint. The term is presently used to describe a volcanic rock, and implies an igneous origin (Glossary of Geology and Related Sciences, 1960, p. 54; 12). This term is useful to describe a subvariety of vitrified "scoria" when used in quotation marks ("clinker").

Clinkertill is a term introduced by Dove in 1922 (p. 338), to describe "scoria". While this term is presently used in Montana to some extent, it has not met with any great acceptance. The term does not appear to possess any descriptive attributes which would promote its acceptance as a substitute for existing names. One might, moreover, suppose the term referred to baked till.

The term, "porcellanite" was suggested by Peithner in 1794, as a substitute for porcelain-jasper, a term applied by Werner, in 1789, to a hard, naturally baked clay which, because of its red color, had been considered a variety of jasper (Tarr, 1938, p. 20). As re-defined by Zirkel in 1894 (p. 775-776), the term porzellanit appears to include all varieties of baked and vitrified sediments formed by burning coal. From the standpoint of priority, therefore, porcellanite (porcelanite;

porcellanit) must be considered the first application of a correct term. Unfortunately, however, this term has subsequently been used to describe other, quite different, rock types. As thus used, the term implies either a contact-metamorphosed marl, or a siliceous shale. The terms, hornfels, siliceous sinter, halleflinta, porcelain-jasper, hornstone, flinty crush-rock, hartschiefer, and pseudo-tachylite have also infringed on the original definition of porcellanite. Therefore, as a result of the confusing nomenclature, porcellanite will be used, herein, only to describe the fine-grained, siliceous variety of "scoria".

Most of the other names proposed to cover the complete range of rock types presently included under "scoria" are either cumbersome, apply only to certain varieties of "scoria", or have not met with acceptance. Most of the names suffer from all three objections.

The term, scoria, as applied to the baked and melted sediments, arose from a misconception as to the origin of the rock. It was thought to have been produced by volcanic action by many early investigators, even though the correct origin was recognized by Lewis and Clark as early as 1805. The Greek word, skoria, (drived from skor, dung), means dross or refuse. The Latin word, scoria, derived from this source, was apparently very early applied to the slag or refuse left after a metal has been smelted from an ore. Similarity of loose, cinder-like lava to smelting slag caused the term to be extended to include this volcanic material. There has never, however, been any purposeful intent to extend the term to include baked and melted sediments. The extension of the term has merely arisen from mistaken identity.

In his recent geography textbook (1963, p. 213), Wills has written:

> For years there has been a tendency to belittle the use of the word "scoria" for that material. But it is scoria, and the well-informed citizen calls it scoria. The 1961 edition of Websters International dictionary lists three meanings of scoria: first, a fused metallic substance found around furnaces; second, "a burned clay or clinker deposit characteristic of burned out coal beds on the western Great Plains"; third, a form of lava rock.

While it is true that the second definition is used in the 1961 edition, it is also true that this same definition is not included in earlier editions of this same dictionary. Therefore, the acceptance of the term, scoria, for baked and melted sediments has come about by usage by a sizeable (?) population (not necessarily geologists) over part of the area of occurrence. From the standpoint of the evolution of language the acceptance of the term, scoria, for these metamorphic rocks cannot be argued. On the other hand, petrographically, scoria is a misnomer as applied to these rocks. The term has always been used by geologists to describe volcanic, pyroclastic ejecta, of igneous origin. It might also be pointed out, that true scoria resembles only one variety of the baked and melted sediments.

Regardless of these objections, the term "scoria" has been retained, in quotation marks, for these metamorphic rocks on the basis of its sole virtue, popular acceptance. The placement of the word within quotes must be established to imply the "so-called" scoria. Better still, would be the attachment of the prefix pseudo- ("pseudo-scoria"), as used by Benson (1952, p. 51) or quasi- ("quasi-scoria"), as suggested by R. A. Caldwell (personal communication, 1965). Still, "pseudo-scoria" or "quasi-scoria" would no better describe the wide range of rock types embraced by "scoria"; moreover, these terms are no more likely to find popular acceptance.

Summary of Classification of "Scoria"

"Scoria" is, thus, the general term embracing diverse types of metamorphic rock, showing effects of metamorphism ranging from oxidation and dehydration to complete fusion, caused by the action of underlying, burning fuels on overlying sediments or sedimentary rocks.

Baked Shale and Baked Mudstone.—These varieties of "scoria" are formed by low-temperature (less than 900°C) metamorphism of claystone, shale, mudstone, and siltstone, or their sedimentary equivalents. The effects of metamorphism are limited to simple oxidation, dehydration, and alteration of micaceous and clay minerals. The rocks reflect the composition of the parent sediments closely, and differ from them mainly in color, state of dehydration, cohesiveness, and texture. Colors may range from white to black, but the prevailing colors are salmon pink, red, reddish orange, and reddish brown. These varieties are the most abundant type of "scoria". They are characteristically composed of a few sharp, clear, silt and fine sand grains of untwinned plagioclase, gypsum, and quartz in a strongly hematitic-stained matrix of these same minerals, plus clay and micaceous minerals. The rare occurrence of cordierite, melilite, tridymite, and slight melting indicate a transitional state to vitrified siltstone or vitrified laminated shale.

Baked Limestone.—Baked limestone is a compact, cohesive, and metamorphosed limestone, marl, or calcarenite which appears otherwise unaltered in hand specimen. In thin section, it is typically composed of denticulate carbonate grains (usually siderite) in a finer mosaic of carbonate and clay minerals. The texture, limited formation of actinolite, and hematitic-staining indicate limited, low-temperature metamorphism.

Baked Sandstone.—Baked sandstones are buff to dark red sandstones which encompass metamorphic effects ranging from simple oxidation to partial fusion (800°C to 1,000°C). These rocks are typically arkosic in composition and color, although the coloration is contributed by iron compounds, rather than by feldspars. With the exception of slight reddening, the baked sandstones typically retain their original identity and texture, until partial fusion occurs. Dominant grain size ranges from fine to very fine sand. The sandstones are typically cross-bedded, and the oxidation of iron compounds to hematite emphasizes this structure in the slightly metamorphosed baked sandstones.

More strongly metamorphosed sandstones characteristically show the formation of more anorthitic rims of plagioclase around original feldspar grains, slight melting of quartz, and the formation of increasing amounts of silica glass in the matrix. Vitrified sandstones may contain tridymite, mullite, melilite, actinolite-tremolite, hypersthene, diopside, cordierite, and other medium to high temperature metamorphic minerals.

Porcellanite.—Porcellanite is a variety of "scoria" that is compact, hard, pastel-colored, and uniformly aphanitic, with the texture and fracture of unglazed porcelain. This variety is often mottled in hand specimen. The rock is composed of a cryptocrystalline matrix of plagioclase, gypsum, quartz, carbonates, silica glass, hematite, micaceous minerals, and clay minerals. Porcellanite typically contains about 15 per cent carbonate (often siderite), and about 15 per cent silica glass. The term as defined here is different from the European definition which has included all varieties of "scoria".

Vitrified Siltstone.—This variety of "scoria" is massive, and transitional between baked siltstone and glassy slag. Vitrified siltstone is typically vesicular and often has a characteristic scoriaceous appearance. The most strongly metamorphosed surface may often melt and develop a surface similar to ropy lava. With increasing vesicularity, the bulk specific gravity may approach one. In thin section, the metamorphic changes are essentially the same as those for the more strongly metamorphosed sandstones. The silica glass content increases with increasing temperature, and cordierite also becomes a common constituent.

Vitrified Laminated Shale.—These metamorphic shales are irregularily banded in various shades of red and green or black. They often have a highly polished surface, but when broken show a dull reddish surface with metallic green-black laminae. The reddish areas are stained by hematite, and the laminae are composed of colorless to dark glass, often darkened by magnetite. The dark bands are sites of selective fusion which have resulted in the formation of glassy laminae. The glassy laminae typically contain semi-oriented microlites which indicate flowage in these areas. Both types of vitrified mudstone rocks are located in the "chimney" zone of "scoria" outcrops.

Glassy Slag.—Glassy slags are relatively rare varieties of "scoria" in which fusion of the parent sediments or sedimentary rocks is complete. These rocks are confined to the fracture zones of "chimneys", where the temperatures were briefly high (more than 1,000°C), and the cooling rate was subsequently rapid. Most of the slag is highly vesicular, and some slags may have a specific gravity less than one. It is this highly vesicular, less metamorphosed form of slag that closely mimics true scoria. In thin section, the isotropic glass ranges from almost clear to black in "color". Magnetite is usually abundant in the silica glass. Most of the slags are more or less devitrified. An occasional specimen may have undergone fusion over a long period of time, resulting in a dense, dark glass which resembles obsidian.

Recrystallized Slag.--Recrystallized slag is a very rare variety of "scoria" in which the cooling rate of the melted material has been slow enough to permit a degree of recrystallization that allows optical identification of some minerals. In hand specimen, recrystallized slag cannot be differentiated from glassy slag. It is only in thin section that incipient crystallization may be observed. The recrystallized slag is typically composed of acicular to lath-like crystals of pyroxene or amphibole, which radiate from centers of crystallization, or from the periphery of vesicles, in a ground mass of clear or devitrified silica glass. Other high-temperature minerals which may appear are plagioclase, magnetite, mullite, melilite, cristobolite, tridymite, sphene, olivine, and wollastonite.

LIGNITE-ASH-"SCORIA"-OVERBURDEN RELATIONSHIPS

General

A large proportion of the 1962-1963 summer field seasons was spent in measuring "scoria" sections in the area of study (Fig. 2, 3, and 4). The purpose of measuring and recording these sections was to attempt to determine the different relationships and ratios between the lignite, ash, "scoria", and overburden. This study area is particularly suitable for this purpose, as it includes the best, and most continuous exposure of the very extensive, HT Butte "Scoria", and some HT Butte Lignite.

Method of Investigation

The sections were measured by locating the lowest ash, and measuring upwards, by use of a hand level, to the soil or unaltered sediment zone. In the area of study, very few "scoria" outcrops were capped by material other than "scoria". An idealized, and complete, "scoria" section usually progresses upward from a thin, slightly baked underclay to a thickness of lignite and ash, or ash only, then to a salmon pink, platy "scoria", which grades into blocky, red "scoria", and finally, into a buff to buff red, baked or pseudocolumnar sandstone. Various forms of more strongly metamorphosed "scoria" (cinder, "clinker", vitrified rock, and glassy slag) may also be present if the section is in close proximity to a "chimney". The sticky, gray to brown underclay is only slightly affected by metamorphism, and the base of the ash, or remaining lignite is, therefore, taken as the base of the section. The ash layer is frequently hidden by "scoria" detritus from the overlying outcrop.

Location of the ash is usually easy when the ash is indurated, or in the form of "semi-coke". In these cases, the ash stands out as an erosion resistant ledge, or may at least be located by the change in slope. The loose, less coherent ash, and lignite remnants often act as a source of water seeps, which frequently indicate their presence. This greater supply of water and chemicals may support vegetation which contrasts with the usually bare "scoria" slopes, and determines the location of ash. Burrowing animals also find the loose, friable ash favorable sites, and their holes and mounds of detritus are useful for ash location. Where outcrops are close together, or the ash projects as a ledge, the ash in the intervening space may often be located by a visual extension from these ash-ledge points of reference. If all of these indicators of the presence of the ash fail, or are lacking, one must resort to trenching. Trenching must also be considered a necessary precaution where multiple burns are suspected, as the lowest ash may otherwise not be obvious.

The absence of ash, or an unreasonably small amount of ash in some areas, is puzzling. The writer believes that the reason for this lack usually lies in the leaching of these soluble compounds, particularily as the ash layer often acts as a water seep. Bowie has also reported (1915, p. 183) an instance where the fine ash was removed in a burning coal mine by the action of water. It is also probable that overburden has slumped over some of the ashes, and hidden them from view. According to Blain (1955, p. 141), the layer of ash may be completely lacking if the coal has burned at a high temperature. This interpretation would appear to be true in some cases, as some of the thickest, and most strongly metamorphosed "scoria" outcrops (Loc. 131, 150, Figure 4) appear to lack ash layers. Dr. W. L. Moore (personal communication, 1963) has also suggested the possibility that some of the ashes may be lost through a "fluing" action. Either the ash was carried away by unusual drafting conditions, or the particular exposure area may have served as a flue, as the lignite burned at another location. That is, as the lignite burned elsewhere in the cavern, the ash was carried away either by peculiar drafting conditions or by the formation of a flue at the particular site of the missing ash. Field investigation would appear to substantiate this unusual loss through "fluing" at a few locations. When the ash layer is missing, the base of the "scoria" section is often found by locating the very distinctive, thin, gray to brown, sticky underclay.

It was originally expected that an isopach map of "scoria"-ash thickness could be constructed from these collected data, but the limited extension of "scoria" into the subsurface made this method of presentation unfeasible. These data are, therefore, presented as columnar sections, using the "ash stratum" as a reference plane (Figs. 9 and 10; or Plates X and XI). Physical correlation of "scoria" may often be from transition zone to transition zone, as petrographic transitions are usually gradual and indistinct.

Previous Work

A number of generalizations concerning the relationship between thickness of lignite, and the amount of ash and "scoria" produced, have appeared in previous literature. Dove said in 1925 (Leonard and others, 1925, p. 21-22), "The size of the coal bed is roughly proportional to the amount of clinker", and, "A 10 or 12 foot coal bed will often give clinker beds 20 or 30 feet in thickness." He further said (p. 22), "Clinker from a lignite bed 10 feet thick may attain a thickness of 30 feet, from a 35 or 40 foot bed it may be 50 or even 60 feet thick, with considerable fused or slag-like material." In 1952, Benson said (p. 52), "When a thick bed of good quality burns the volume of the bed decreases to about 20 per cent of the original volume." Fisher has also commented (1953), "The thickness of the ash is about one-quarter to one-fifth that of the original coal bed." May (1954, p. 19) has stated that the thickness of his "clinker zone" is roughly proportional to the original thickness of the lignite, but he recognized the variation possible, due to "overburden conditions". As with most generalizations, when examined in detail these disclose many exceptions.

Present Investigation

Validity of Generalizations

These observations concerning lignite-ash relationships were apparently taken from a few outcrops in which fires in the lignite had gradually burned out, so that the thickness of the lignite, and the thickness of the ash produced could be compared. The writer has observed a number of these areas in which lignite has burned to ash, both in the area of study (Loc. 17, 18, 64, 82, and 84, Fig. 3; Loc. 101, 102, Fig. 4), and in surrounding areas. In a total of some 25 occurrences of burned lignite outcrops, all, without exception, were burned in open-faced, oxidizing conditions. In all cases, the degree of metamorphism was slight, and in most cases, the thickness of "scoria" produced was limited. Therefore, while the generalization that the thickness of ash is usually about one-fourth to one-fifth of the original thickness of lignite, appears to be in the correct order of magnitude, the statement must be limited to those lignites which have burned under oxidizing conditions.

Even the statement that the thickness of lignite is roughly proportional to the thickness of ash or clinkerized material, is subject to exceptions. This generalization does not consider either the purity of coal or the conditions of burning. It is well known that pure lignites burn with a minimum of ash, while impure lignites (containing shale partings, stumps, FeS_2, and various sulfates) burn with maximum formation of ash and clinkerized material. It is also obvious, for reasons presented in an earlier chapter on the formation of "scoria", that the conditions of burning also have a strong influence on the amount of ash produced from a given quantity of lignite. In the reducing-distilling zone of burning, thick coherent masses of "semi-coke" are typically formed, while in the oxidizing zone, variable thicknesses of ash are produced, depending on the purity of the lignite.

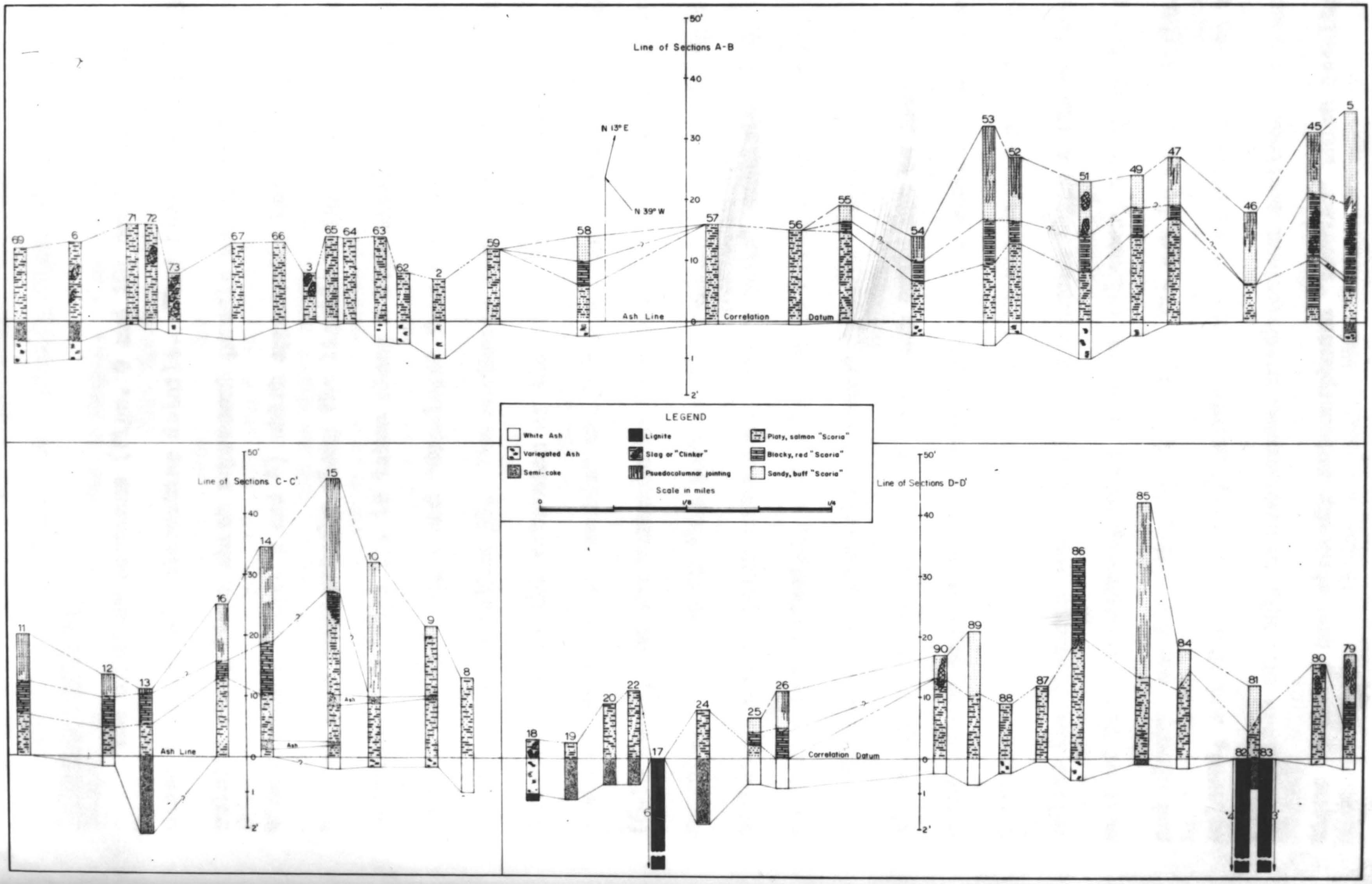
Statements as to the thickness of "scoria" produced from a given thickness of lignite, and the resulting degree of metamorphism are far more dependent on conditions of burning, and overburden thickness, than on thickness of lignite. It has also been observed that very thick beds of "scoria" are usually the result of multiple burns of separated lignites, rather than extreme thicknesses of lignite. It might be pointed out again, moreover, that the very thick Harmon lignite, which is presently burning, has produced insignificant amounts of "scoria", and not unusual thicknesses of ash.

If these generalizations were to be extended to "persistent scorias" such as the HT Butte "Scoria", several further assumptions would have to be made. The first assumption would have to be that the overburden was relatively uniform in thickness to provide uniform conditions of "scoria" formation. In previous discussion it has been suggested that the formation of the HT Butte "Scoria" is related to terrace formation, and that the terrace provided a thickness of overburden which permitted extensive, and relatively continuous, formation of "scoria". This thickness was apparently greater than 25 feet and less than 100 feet. It is very tempting to suggest a minimum thickness somewhat in excess of the thickest "scoria" section in the study area (approximately 50 feet; Loc. 15, 18, Fig. 3; Loc. 113, Fig. 4), but considerable variation in minimal thickness of overburden is apparent. There is great variation in the degree of metamorphism, and thickness of "scoria", as shown on the cross-sections (Figs. 9 and 10; or Plates X and XI). As the degree of metamorphism, and resulting thickness of "scoria", is most dependent on conditions of burning, and conditions of burning are directly related to overburden thickness, it follows that variation in thickness of overburden existed. Thus, the assumption of a uniform thickness of overburden is not valid.

The second assumption would have to be that the few remaining outcrops of HT Butte Lignite in the area of study (Loc. 17, 82, 83, Fig. 3) are indicative of the general thickness of the HT Butte Lignite (approximately six feet maximum in the area of study), and that the thickness of the lignite is relatively uniform. Many of the thinner lignites are definitely not uniform in thickness; and, in fact, are usually pod- or lens-like in shape. These lignites were apparently deposited in swamps or bogs of limited extent, which were periodically shifted about as they filled. On the other hand, a lignite such as the HT Butte Lignite, which apparently had an extent of 2,000 square miles or more must have been rather continuous. According to Leonard (1925, p. 52-54), however, the HT Butte Lignite has a thickness of five feet in the Tepee Buttes, 15 feet in Bullion Butte, and 17 feet near the north boundary of Theodore Roosevelt National Memorial Park, South Unit. It is obvious therefore, that there is considerable variation in the thickness of the HT Butte Lignite, even though the change in thickness might be relatively gradual in the area of study. Thus, there is little evidence to determine the uniformity of thickness of the HT Butte Lignite in the area of study.

If the generalization that the thickness of "scoria" is directly proportional to the thickness of lignite was true, then the thickest "scoria" would be expected in the vicinity of the thickest lignites. This does not necessarily appear to be true in the case of the HT Butte Lignite. At locations 82 and 83 (Fig. 9; Plate X) the lignite is four feet or less in thickness, yet one of the thickest "scoria" outcrops (Loc. 85) is located within 500 feet of this lignite outcrop. On the other hand, the six foot thickness of lignite at location 17 is surrounded by relatively thin "scoria" outcrops (Fig. 9; Plate X). It might also be mentioned, once again, that the presently burning, thick, Harmon Lignite has not produced significant amounts of "scoria". Thus, the direct relationship between thickness of lignite and thickness of "scoria" does not appear to be valid. It would also appear that four to six feet of suitable lignite is sufficient to produce thick "scoria",

Fig. 9.—Columnar sections of HT Butte "Scoria", ash, and HT Butte Lignite from Area I (Figs. 2 and 3). Enlargement of Fig. 9, as Plate I, may be found in the envelope on the back cover.



Line of Sections A-B
N 13° E
N 39° W
Ash Line
Correlation
Datum
Line of Sections C-C'
Line of Sections D-D'
Correlation Datum
LEGEND
White Ash
Variegated Ash
Semi-coke
Lignite
Slag or "Clinker"
Psuedocolumnar jointing
Platy, salmon "Scoria"
Blocky, red "Scoria"
Sandy, buff "Scoria"
Scale in miles
0
1/8
1/4

with appropriate overburden conditions.

<u>Columnar Sections</u>

The columnar sections (Figs. 9 and 10; or Plates X and XI) disclose a number of interesting details. They have been physically correlated along lines which represent genetic units, that is, along individual ridges (Figs. 3 and 4) which apparently burned progressively and more or less continuously along the lignite beds. The line of columnar sections, A-B (Fig. 3), is taken along a high cliff which lies southwest of the Park Road, and "dog-legs" from a direction of N.13°E. to N.39°W., near location 58. The northerly section of the line passes obliquely across the extension of the other lines of sections. It consists of outcrops of "scoria" which are rather uniform in thickness (6-16 feet), and are variable in thickness of ash, and degree of metamorphism. The ash in this part of the section is typically dark gray to black, and slightly indurated. The "scoria" consists mainly of salmon pink, platy material, with subordinate blocky, red "scoria", and some clinker-like material. A second "scoria" layer lies below the ash at locations 69 and 6, but the lower ash could not be located. The southeastern segment of this same line is more varied, both in the thickness of "scoria" (14-35 feet), and in the degree of metamorphism. Unlike the northeastern segment, this segment shows a strong development of baked sandstone, which is often columnar, overlying the platy and blocky "scoria" (Fig. 9; Plate X). The ash is usually light-colored, and thin. The ash/"scoria" ratio is considerably less than in the less strongly metamorphosed northeastern section. Columnar sections 45 and 5 are strongly metamorphosed "scorias" which resulted from burning of two, separated, lignite beds.

The line of sections C-C' (Fig. 9; Plate X) lies across a deep valley to the northeast from line A-B, essentially parallel to the northwestern segment of A-B. This cross-section includes the thickest, and most strongly metamorphosed "scoria" in Area I (Figs. 2 and 3). Columnar sections 14, 15, 10, and 9 represent outcrops which are the result of the burning of two or three separated layers of lignite. Columnar section 15 (Scoria Point, Theodore Roosevelt National Memorial Park, Fig. 3), contains three separated ash layers, and it has the highest ash/"scoria" ratio of the four columnar sections. Even so, the maximum ash/"scoria" ratio (0.05) is relatively small in comparison to most thinner and less metamorphosed "scoria" outcrops. An extreme example of this may be seen in columnar section 13, which lies less than 1,000 feet to the northwest. In this outcrop, the "scoria" is considerably thinner (14 vs. 46 feet) than at Scoria Point, but the very thick formation of strongly indurated, black "semi-coke" results in an ash/"scoria" ratio of 0.2. While this example cannot be considered characteristic, it does indicate the extreme variation that may occur, and the fallacy of the assumption that ash layer thickness is roughly proportional to lignite thickness, and that it may be proportional to "scoria" thickness. Columnar jointing occurs in all of the outcrops along line C-C'.

The line of sections D-D' (Fig. 9; Plate X) is located in the next ridge to the northeast of C-C', across the intervening valley. This cross-section includes three outcrops of HT Butte lignite (Loc. 17, 82, 83) which have a range of thickness from three to six feet. The outcrops which lie to the extreme northwest are strongly eroded, and are not directly comparable to other outcrops in the line of sections D-D'. All of the outcrops in all cross-sections in Area I (Fig. 2) show a tendency to thicken towards the direction of headward erosion (southeast). It is probable that erosion was more advanced towards the mouths of these drainages (northwest) before the formation of "scoria". It is also probable that fires were initiated towards the mouths of these drainages where the lignite was initially dissected. If this is true, the "scoria" outcrops which lie to the northwest, parallel to the drainage, would have undergone a longer period of more active erosion, but at a lesser rate, than those still unmetamorphosed sediments which lie to the southeast. It is unknown to what extent these factors counteract one another, but they must be considered in interpreting the data presented in some columnar sections. If the original thickness of the overburden was considerably greater than necessary for minimal optimum burning conditions, as it may have been, the differential rate of erosion between the "scoria" and sediment areas would probably be of little significance. In this case, the simple generalization, that "scoria" outcrops nearest the mouths of the drainages underwent greater erosion, would stand.

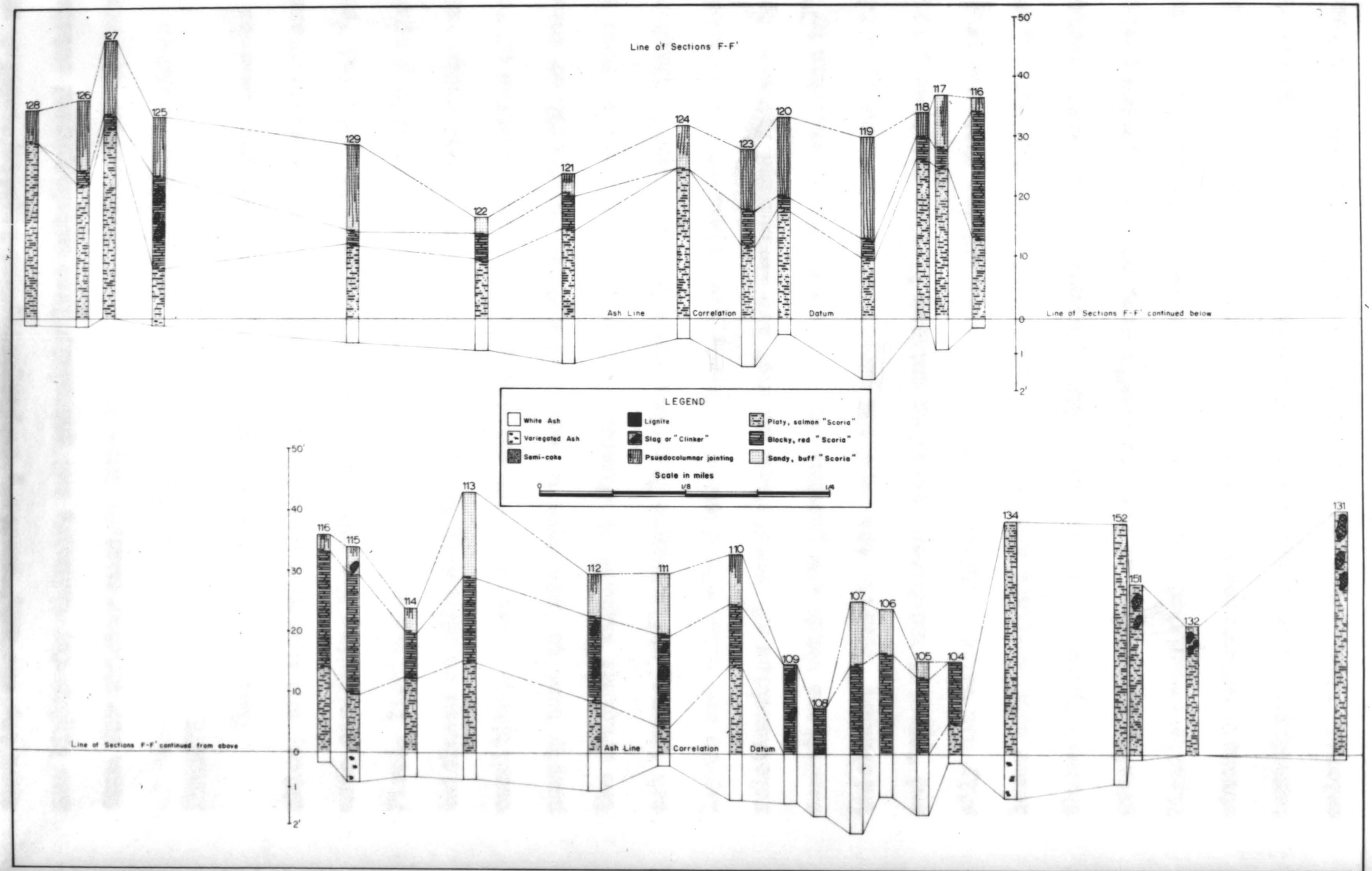
The outcrops (Loc. 24, 25, 26, Fig. 9; Plate X) southeast of the first HT Butte Lignite outcrop contain rather thick, dark violet to black, slightly indurated ash, and have a high ash/"scoria" ratio (0.07 to 0.25). The thicker and more strongly metamorphosed outcrops (Loc. 86, 85, 84, 80, 79) contain thin layers of light colored, variegated white, red, and yellow ash, and have low ash/"scoria" ratios (0.005 to 0.02). Outcrop 81 is located between two outcrops of HT Butte Lignite which have a maximum thickness of about 5.5 feet. The outcrop is conposed of 12 feet of platy tan and salmon pink "scoria", and contains 10 inches of dark, hard, ledgy ash. This results in an ash/"scoria" ratio of 0.09, and an ash/lignite ratio of 0.18. The lignite/"scoria" ratio for this same outcrop is 0.45. All three of these ratios are greater than are characteristic for thicker, and more strongly metamorphosed outcrops, an observation which also is generally valid for the previously discussed cross-sections.

Outcrops 88 and 89 (Fig. 3) are especially interesting in that they demonstrate the limited penetration of burning, and subsequent limited formation of "scoria" into the subsurface. The "scoria" outcrops have persisted as ridges, but the unmetamorphosed sediments behind them have eroded away to expose fresh lignite. In these outcrops, burning could not have penetrated more than twenty feet. This same relationship is shown even more strikingly at location 93 (Plate VIII, Fig. 6), southwest of line A-B (Fig. 3). Near this location (Loc. 92), the HT Butte Lignite is again exposed, and it is composed of a lower four foot layer and an upper two foot layer. The line of columnar sections E-E' shows less distinct variation, but the same general observations may be made. The thinner "scoria" beds typically have higher ash/"scoria" ratios. If uniform thickness of lignite may be assumed, these thinner beds also typically have higher ash/lignite and lignite/"scoria" ratios than do the thicker beds. One general exception may be noted, in that the very strongly metamorphosed "scoria" outcrops (chimney zones) may often have rather high ratios. These outcrops are characterized by thick, dark-colored, "semi-coke", ash layers.

Columnar sections 5, 15, and 85 (Fig. 9; Plate X) represent the thickest, and most strongly metamorphosed "scoria" outcrops. These outcrops are all located near the southeastern end of the cross-sections in Area I (Fig. 3). Apparently the thickness of overburden was near-optimum for burning conditions which produced maximum thicknesses of strongly metamorphosed "scoria". Thicknesses of "scoria" outcrops decrease to the northwest and southeast away from these outcrops, which indicates that irregularities must have existed in the overburden thickness at the time of burning. It is also probable that the lignite separated into several layers, and possibly thickened, as outcrops at locations 5 and 15 contain several ashes.

The long, almost straight-line series of outcrops measured in Area II (Figs. 3 and 4), are located in a high bluff which parallels the trend (N.69°W.) of the underfit Sully Creek. The thickness of "scoria" and ash is generally rather uniform (Fig. 10; Plate XI). The ash is typically thicker, and less coherent than in the cross-sections previously discussed. The ash is also characteristically light-colored. The conditions of burning which produced these outcrops must have been very uniform. "Scoria" thickness typically ranges from about 20 to 43 feet, with but few exceptions. The degree of metamorphism appears to be somewhat less than that encountered in comparably thick outcrops in Area I. A number of comparatively thick outcrops in the southeastern segment of the series are composed entirely of salmon pink platy "scoria". Pseudocolumnar sandstones only occur in the thicker outcrops in the northwestern part of line F-F' (Fig. 10; Plate XI). The only outcrop of HT Butte lignite in this immediate area is at location 102 (Fig. 4). At this location the lignite is about 4.5 feet thick, and it is transitional to an ash layer with overlying "scoria" at location 101. The same general relationships may be seen in this area,

Fig. 10.—Columnar sections of HT Butte "Scoria" and ash from Area II (Figs. 2 and 4). Enlargement of Fig. 10, as Plate XI, may be found in the envelope on the back cover.



Line of Sections F-F'
128
126
127
125
129
122
121
124
123
120
119
118
117
116
Ash Line
Correlation
Datum
Line of Sections F-F' continued below
50'
40
30
20
10
0
1
2'
LEGEND
White Ash
Variegated Ash
Semi-coke
Lignite
Slag or "Clinker"
Psuedocolumnar jointing
Platy, salmon "Scoria"
Blocky, red "Scoria"
Sandy, buff "Scoria"
Scale in miles
0
1/8
1/4
Line of Sections F-F' continued from above
116
115
114
113
112
111
110
109
108
107
106
105
104
134
152
151
132
131
Ash Line
Correlation
Datum

that is, the ash/"scoria", ash/lignite, and lignite/"scoria" ratios are higher for thinner, and generally less metamorphosed outcrops than for thicker ones.

Summary

Thus, while there are many factors to consider, numerous variables, and numerous exceptions, certain limited generalizations may be made concerning the relationships between lignite, ash, and "scoria". First, lignites of similar purity tend to show a roughly proportional thickness relationship to the ash formed, when burned under oxidizing conditions. Second, under oxidizing conditions, lignites of "average" purity tend to burn down to ash layers about one-fourth or one-fifth of the original lignite thickness. Extremely pure lignites form thinner ash layers, while impure lignites may form considerably thicker ash layers and clinkerized zones. Third, the thickness and metamorphic relationships of "persistent scoria" are influenced far more by burning conditions which are governed by overburden thickness, than by lignite thickness. Fourth, the expected proportional relationship between ash and "scoria" thickness, assuming uniform lignite thickness, is generally not valid. Thicker "persistent scorias" are characterized by lower ash/"scoria", ash/lignite, and lignite/"scoria" ratios, than are thinner "persistent scorias". This phenomenon apparently reflects the greater efficiency of burning conditions, and the greater purity of lignite associated with these thicker "persistent scorias". The very strongly metamorphosed "scorias" ("chimney" zones) generally have intermediate ratios, and are characterized by relatively thick, dark-colored, "semi-coke" layers. Fifth, extreme thicknesses of "scoria" are usually the result of the burning of several separated lignites, rather than the burning of a single very thick lignite. Sixth, in some areas the amount of erosion, both before and after the formation of "scoria" must be interpreted before specific statements can be made regarding "scoria"-ash-lignite relationships.

EFFECTS OF "SCORIA" ON TOPOGRAPHY

The more obvious topographic effects of the burning of lignite and subsequent formation of "scoria" are recognized by even the most casual visitor in the badlands of the Little Missouri. The most characteristic "scoria"-influenced topography lies in a north-south band along the Little Missouri River. This badland area, in the area of investigation, may extend as far as 10 miles to the east of the river, and an equal distance to the west. The Little Missouri Badlands are characterized over much of their extent by bright pink and red "scoria" layers which lie near the tops of the Little Missouri bluffs, less persistent "scoria" layers at lower levels in the bluffs, resistant "scoria" bordered plateaus, "scoria" capped ridges and divides, "scoria" capped buttes, and sharp pinnacles capped by "scoria". The panorama presented, is one of strongly dissected terraces with steep-sided, denuded buff and tan slopes, interlayered, and capped by bright pink and red "scoria". Only the plateaus, floodplain, and uplands bear extensive vegetation.

Burning of lignite has had two general effects on the topography of the area. It has lowered the overlying strata by an amount equal to the lignite burned, and has loosened and broken the overlying overburden. The "scoria" which may be formed by the burning of lignite, however, plays no small role in retarding erosion and maintaining the rugged topography. The "scoria" resists erosion of the slope by its improved cohesiveness and hardness, as compared to the unconsolidated sediments, and by its gross permeability which permits water to percolate through the outcrop into the underlying sediment, retarding the "sheetwash effect". Erosion is mainly confined to sediments of the lower, underlying slope which may eventually oversteepen, and cause collapse of the overlying "scoria". This action is usually self-defeating, however, as the intensely fractured "scoria" outcrop eventually covers the lower slope with talus. In the case of large "scoria" outcrops this talus slope may persist for 50 or 60 feet below the base of the outcrop. The talus slope further retards erosion by providing a more resistant surface, and an increased, permeable surface for percolation which reduces the amount and velocity of runoff. The effectiveness of these processes may be seen in the persistence of "lumpy"-like, "scoria" buttes on the old upland surface.

The existence of "chimneys", which often stand as pinnacles above the surrounding area is an interesting feature of the Little Missouri Badlands. These more or less circular, brecciated columns often stand well above the less strongly metamorphosed and consequently, less erosion resistant "scoria" (Plate IX, Fig. 4). In some areas, old "chimneys" stand above the grassed upland plain, without a suggestion of less strongly metamorphosed "scoria" around them. In other locations, particularily southeast of Sentinel Butte, these old "chimneys" form low ridges which are the only remnants of "scoria"-forming activity. Some of the "chimney" masses have tumbled from the ridges and now lie as isolated vitrified and brecciated "scoria" blocks on the grassy uplands. The best example of this form of "scoria", and extreme metamorphism, is found at location 130 (Fig. 4). This very large outcrop

PLATE VIII

EFFECTS OF "SCORIA" ON TOPOGRAPHY

Fig. 1.—View looking northeast across part of Sentinel Butte towards the beginning of the Little Missouri Badlands. Projection of Sentinel Butte in the foreground shows extreme thickness of "scoria" and multiple ashes.

Fig. 2.—View of the typical Little Missouri Badlands topography. Viewed looking north from Highway 10 into Theodore Roosevelt National Memorial Park.

Fig. 3.—"Hump" topography (sec. 17, T. 140 N., R. 105 W.) caused by "scoria" capping on buttes on the upland surface which has undergone a long period of erosion.

Fig. 4.—Cuesta-shaped ridge showing limited penetration of "scoria" into the subsurface. Ridge located along the southeastern half of line of sections F-F' in Area II (Figs. 2 and 4).

Fig. 5.—"Hump" topography protected by a "scoria" capping. Located on the upland surface in sec. 17, T. 140 N., R. 105 W., northwest of Sentinel Butte, North Dakota.

Fig. 6.—Wall-like ridge of "scoria" showing very limited penetration of "scoria" into the subsurface. (Loc. 93, Fig. 3.)

Fig. 7.—Extremely large "chimney" composed of strongly metamorphosed "scoria" (Loc. 130, Fig. 4).

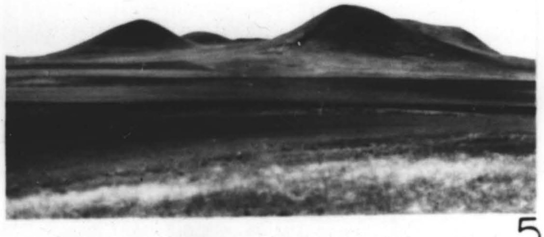
Fig. 8.—Detailed view of the same outcrop showing brecciation and flowage of the glassy appearing "scoria".


1


2


3


4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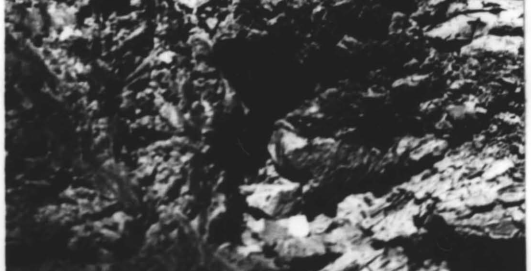
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contains a 50 foot long by 20 foot high surface area of extremely metamorphosed, glazed and vitrified "scoria" (Plate VIII, Figs. 7 and 8. This outcrop displays the most intensive metamorphism of any known to the writer in North Dakota.

Another interesting topographic feature is the development of cuesta-shaped "scoria" ridges. This form is common to most "scoria" ridges, but is most dramatically displayed along the ridge (Plate VIII, Fig. 4) in Area II (Fig. 4). This tendency towards the cuesta form is caused by differential erosion between "scoria" and the unmetamorphosed sediments behind the outcrop. The gentle slope behind the "scoria" outcrop is often eroded to a level which exposes the unburned lignite. This phenomenon also apparently accounts for the unequal development of "scoria" on opposite sides of a narrow ridge. If lignite on one side of a ridge burns first, with subsequent formation of "scoria", differential erosion may tend to erode away the optimum thickness of overburden necessary for the formation of thick "scoria" on the opposite side of the ridge.

A further development of this process may be seen in some areas (Loc. 93, Fig. 3) where the "scoria" outcrop has been etched out by erosion to form a wall-like ridge in front of a butte (Plate VIII, Fig. 7). Some of these outcrops are thinner than they are high (20-40 feet), which demonstrates the limited penetration of "scoria" into the subsurface.

The effects of "scoria" on topography are not confined only to badland areas. Some features are not characterized by steep bare slopes, and flat or pointed summits. "Hump" topography (Plate VIII, Figs. 3 and 5) is characteristic of many upland areas, and particularly in some parts of the area around Glen Ullin. This variation in "scoria"-influenced topography can best be observed from Sentinel Butte. Looking to the north and northwest, a rolling, grassy plain may be observed for several miles which is occasionally dotted with rather large (50 to 150 foot high) broadly conical, round-topped, grassed "humps". Some of these "humps" are capped by massive unmetamorphosed sandstones, but the majority are capped by strongly weathered "scoria". These "humps" on the highest upland terrace may well have been some of the earliest "scoria" formed, and as such, have undergone a prolonged period of erosion. Almost all of the less strongly metamorphosed "scoria" has been reduced to fine detritus, and only remnants of "chimneys" occasionally remain. Many "chimney" masses lie about on the rolling upland, indicating that once this protective cap was lost, the "humps" were rapidly reduced to the level of the rolling plain.

The topographic surface which lies to the south and southwest of Sentinel Butte presents a considerably different appearance from that to the north. The topographic surface in this area is characterized by numerous, low, "chimney"-capped ridges. Most of these ridges are capped by strongly metamorphosed "scoria" which forms jagged ridges. There is little indication of less metamorphosed "scoria" on these ridges. Many of the "chimney"-like masses, which may have a weight of several tons, have rolled down onto the prairie. A few of these "scoria" boulders have been used by cattle for rubbing blocks ("buffalo boulders"), and have acquired a fine sheen in the process. Metamorphism must have been very intensive in this region as the "chimney" blocks are relatively continuous for several miles. These "chimneys" were "let down" by long-continued erosion from initially higher ridges.

Looking to the northeast, east, and southeast from Sentinel Butte a strong transition may be seen between the rolling, grassy upland plain and the rugged, denuded, sharp slope, brilliant-hued topography which begins with the "breaks" of the Little Missouri Badlands. The badland topography (Plate VIII, Fig. 2) continues for about 20 miles, then changes abruptly once more to rolling upland topography in the vicinity of Fryburg, North Dakota.

JOINTING AND FRACTURING IN "SCORIA"

Almost all "scoria" outcrops are characterized by extreme fracturing and jointing resulting from the relief of contractional stress subsequent to heating. The general effect of heating is gradual expansion of the rock mass, but subsequent cooling takes place at a more rapid, and unequal rate, which induces a stress field that may be relieved by rupture. Fracturing is usually so intense and complete in the outcrop that unbroken blocks of "scoria" having a dimension greater than two feet are extremely rare. Only the rare, glassy and extremely vitrified "scorias" are relatively unjointed.

The most common type of fracturing is the platy fracture associated with baked shales. This type of fracturing is usually localized within the baked shale zone, and is apparently related to the original bedding. The dominant planes of fracture are essentially horizontal, although highly variable attitudes may occur locally.

The overlying massive siltstones commonly break into either tabular or blocky units, and are often the largest blocks in a "scoria" outcrop. Porcellanite often breaks into relatively large, equidemensional blocks, which may, in addition, show a semi-conchoidal fracture. Conchoidal fractures are also common to some glassy slags. The vertical breaking surfaces on the blocky "scorias" are often undulating.

Tabular jointing in the siltstones is usually transitional upward into sheeted jointing in the baked sandstone layer. These baked sandstone "sheets" may have a thickness of from one to six inches, and a more or less equidemensional surface area of several square feet. The platy surface is usually horizontal, but may occasionally be inclined, apparently in isothermal response to temperature during cooling. Jointing bears no relationship to cross-bedding, and in fact, is almost always oblique to this structure (Plate II, Figs. 1 and 3). Sheeted jointing is often transitional, both laterally and vertically, to pseudocolumnar jointing.

Pseudocolumnar Jointing

Columnar jointing is an unusual jointing phenomenon which is generally associated with igneous rocks. Allen was apparently the first person to describe this "prismatic structure" in metamorphosed sandstones (1874, p. 251). Laird has coined (1950, p. 14) the term "pseudocolumnar jointing" for this phenomenon described from the South Unit of Theodore Roosevelt National Memorial Park. While columnar jointing in baked sandstone is caused by essentially the same process as the same phenomenon in igneous rocks, and while the term has never been confined to igneous rocks, it is desirable to differentiate this occurrence in baked sandstone from the more common association with igneous rock. Therefore, the term pseudocolumnar jointing has been adopted in this paper.

Pseudocolumnar jointing is not a characteristic feature of all "scoria" outcrops, but it is common in some areas. This phenomenon is characteristic of the more strongly metamorphosed, thick, and "persistent scoria" outcrops. It only occurs where metamorphism has been intense enough to effect the sandstones in their usual position, well above the burning lignite, or where sandstones are in close proximity to the burning lignite. In the "common" depositional sequence, predominant sand-sized sediments usually lie from 15 to 30 feet above the lignite. Erosion, both before and after the formation of "scoria" also accounts for the lack of pseudocolumnar jointing in some areas.

Apparently, upon cooling, the baked sandstones tended to break into irregular, polygonal columns with their long axis approximately perpendicular to the surface of greatest cooling. The columns characteristically cut across the bedding planes, as the surface of greatest cooling was usually either the top or exposed side of the outcrop. The columns range in diameter from a fraction of an inch to about eight inches, and may have a length of several feet (Plate IX, Fig. 5). Diameters from one to three inches, and lengths from six to 12 inches are the most common range of dimension. Some of the columns may also be rather smoothly curved along their length (Plate IX, Fig. 3). Pseudocolumnar jointing occurs most commonly in the coarsest, buff to light red colored sandstones. The most perfect columns are developed in the fine-grained, red sandstone and siltstone. The coarser sandstone usually forms larger columns.

Pseudocolumnar jointing is confined almost exclusively to sandstones and very coarse-grained siltstones. The rare exceptions in finer-grained sediments appear more related to deep desiccation cracking, than to contraction after cooling. The reason for this limitation appears to lie in the relative composition of the sediments. A number of thin sections were prepared from six different columnals collected in different locations, along with the underlying non-columnar "scoria". The columnar sandstones had a typical baked sandstone composition, and

PLATE IX

PSEUDOCOLUMNAR JOINTING

Fig. 1.—Cross-bedded baked sandstone column (Loc. 19). Note that jointing has cut across the bedding planes. (One inch reference grid.)

Fig. 2.—Pseudocolumnar jointing developed perpendicular to the nearly horizontal cooling surface in a baked sandstone outcrop. (SE¼sec. 33, T. 141 N., R. 101 W.)

Fig. 3.—Gently curving columns of baked sandstone showing bedding oblique to the direction of jointing. Located near the outcrop above (Fig. 2) in Theodore Roosevelt National Memorial Park near Wind Canyon.

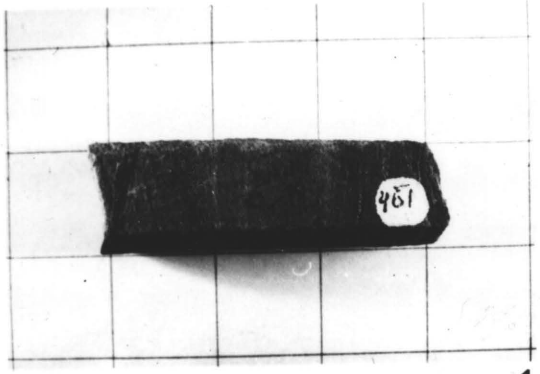
Fig. 4.—"Chimney" composed of strongly metamorphosed "scoria" which has resisted erosion better than surrounding, slightly metamorphosed "scoria" (near Loc. 84, Fig. 3).

Fig. 5.—Long (one to four feet), thin columns of baked sandstone located near Wind Canyon (SE¼sec. 33, T. 141 N., R. 101 W.).

Fig. 6.—Outcrop of pseudocolumnar jointed sandstone showing deviation from hexagonal outline and curving faces of individual columns (SE¼sec. 33, T. 141 N., R. 101 W.).

Fig. 7.—Pseudocolumnar jointing developed perpendicular to a fracture showing later fusion at the tips of the columns (SE¼sec. 33, T. 141 N., R. 101 W.).

were typically weakly to moderately metamorphosed. The main difference between the columnar sandstones and non-columnar "scoria" was the high, quartz/clay mineral-plagioclase ratio of the baked and columnar sandstones in comparison to the finer-grained, non-columnar "scoria". Quartz is unusual among the common rock-forming minerals in having a very high thermal expansion (8×10^{-6} per °C parallel to the c-axis, and perpendicular, 5.4×10^{-6} per °C). On the other hand, fused silica has the lowest thermal expansion, namely 0.5×10^{-6} per °C (Rosenthal, 1949, p. 75). Consequently, according to Rosenthal (p. 75), if quartz particles are lying at random, the average expansion is about fifteen times greater than for fused quartz. Quartz also undergoes a considerable increase in volume at relatively low temperatures. According to the Handbook of Physical Constants (Birch and others, 1942, p. 35), quartz undergoes a change of volume of 4.55 per cent with the transition from the alpha to beta form at 573°C. This compares to a range of expansion from 0.78 to 1.85 per cent for other common rock-forming minerals at approximately the same temperature (600°C). Therefore, as a result of the comparatively high content of quartz and low content of clay-sized minerals and plagioclase (which tend to fuse), the baked columnar sandstones have expanded greatly with gradual heating. Upon rapid cooling, however, the resulting contractional stresses have been relieved by fracturing. The finer metamorphosed sediments, as a result of lower quartz content, and the higher content of clay-sized, easily fused minerals, have not expanded as much. At relatively low temperatures these clay and micaceous minerals have undergone incipient fusion to form a higher percentage of less thermally expansible compounds (feldspars and silica glass). Therefore, the finer-grained



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sediments undergo limited expansion upon heating, and subsequently, limited contraction upon cooling.

When the sandstone is heated to vitrification temperature, however, pseudocolumnar jointing does not occur. The quartz is melted to silica glass, and further expansion and contraction are sharply reduced. This phenomenon is demonstrated at an outcrop located in the SE¼ of sec. 33, T. 141 N., R. 101 W. At this outcrop small sandstone columnals have formed perpendicular to a vertical fracture in a "chimney" zone (Plate IX, Fig. 7). Later, apparently, the temperature at the fracture reached the point of vitrification and melted the tips of the sandstone columnals. The tips of the columnals fused together, and did not re-fracture into columnals upon cooling. Thus, while pseudocolumnar jointing is characteristic of strongly metamorphosed outcrops (in order that metamorphic effects may extend to the distantly overlying sandstones), the columnar sandstones are not strongly metamorphosed. Pseudocolumnar jointing, therefore, probably forms at temperatures in excess of 573°C and below the vitrification point of sandstone (approximately 1,000°C).

Columnar jointing is usually explained as being due to the development of centers of contraction at equally-spaced intervals on the cooling surfaces. According to Tyrrell (1958, p. 41), lines joining these centers are the directions of greatest tensile stress, and when the rigidity of the rock is overcome, cracks appear perpendicularily to these lines. The cracks will intersect to enclose an hexagonal area. This theory works well for some very homogenous materials when subjected to uniform heat distribution, but recent researchers have questioned the validity of this approach as applied to rocks.

According to Beard (1959, p. 381), in many areas of columnar jointing, hexagonal columns are not as common as would supposed from theory. The only exceptions noted were Devils Postpile, California and Giants Causeway, Ireland, where cooling conditions were nearly ideal. This lack of predominant hexagonal jointing is certainly true of pseudo-columnar jointing in the area studied by the writer. Several pseudo-columnar outcrops (Loc. 14, 15, 23; Fig. 3) were analysed in detail to determine jointing relationships and the predominance of polygonal form. Approximately 60 per cent of the columns in each outcrop were bordered by five sides, 20 per cent to 30 per cent were four-sided, and only about 10 per cent of the columns were hexagonal. Columns with more than six sides were extremely rare, and those with less than four sides were uncommon. The very common pentagonal forms usually had either one or two curved faces. Four-sided forms were usually transitional to "sheet" jointing, and may have been secondarily influenced by bedding. Hexagonal prisms are usually straight-sided, but the columns often show a tendency towards flattening.

At least two factors are necessary for the formation of hexagonal columns by the process previously mentioned. They are homogeneity, and isothermal distribution of heat. These factors are highly unlikely in the baked sandstones. Any deviation from these two conditions would tend to cause non-simultaneous propagation of tension cracks. It would appear to the writer that non-simultaneous fracturing would cause later-formed tension cracks to be influenced by the stress field of earlier-formed cracks. The common occurrence of curved cracks which joined other cracks at right angles appear to confirm this tendency.

According to Lachenbruch (1962, p. 45), a tension crack tends to propagate in the direction perpendicular to maximum tension, and therefore, a crack advancing in an oblique direction will tend toward the normal to a pre-existing crack after entering the zone of stress relief. The same writer has stated (p. 50), "if a crack is sinuous, the residual tangential stress attains maxima on the convex sides of bends which are therefore favored as sites of intersection by secondary cracks". He has further suggested (p. 51), that non-orthogonal crack patterns could be produced by this process. It has also been suggested that most non-orthogonal intersections form by the bifurcation of growing cracks (Lachenbruch, 1962, p. 52).

The writer has subjected sawn blocks of sandstone to temperatures approaching vitrification in an electric furnace. Some of these blocks have tended to develop bifurcating cracks, and all of the cracks narrowed at one end, a condition leading to bifurcation. These experiments, and field evidence of the same phenomenon, would indicate that some cracks formed in this way. The writer believes that the general lack of three element intersections at approximately 120°, and the unlikely occurrence of uniform heat distribution and homogeneity do not favor a hexagonal fracturing system as the dominant column-forming process in most outcrops. The very common curved cracks and orthogonal intersections would indicate that the interaction of stress fields is an important influence in column formation. It is also likely that many cracks are formed by bifurcation, as implied by experimental evidence, and as shown by the occurrence of cracks bifurcating from a stem crack at angles other than 120° in the outcrops.

Determination of the major structural elements related to jointing was attempted by recording the attitudes of fractures in several outcrops (Loc. 14, 15, 23). It may be seen from the area map (Fig. 2) that the trends of the major drainages (Paddock, Sheep, Railroad, and Sully Creeks) range from about N. 70°W. to N. 60°W. It was expected, therefore, that the non-horizontal cooling faces, being related to dissection, would also reflect these trends. To a certain extent this relationship holds, but most of the pseudocolumnar outcrops are salients which project out from the general line of outcrop. Thus, the cooling surfaces are oriented around the periphery of the projecting outcrop. Cooling surfaces on the outcrop at location 15, for example, are oriented through the range N. 30°W. to N. 65°W. Cooling surface attitudes plotted from this same outcrop on an equal area net and solved by stereographic projection indicate two major attitudes for the cooling surfaces, namely, N. 62°W., dipping 81° southwest, and N. 38°W., dipping 56° southwest. The attitudes of columnals, plotted and solved in the same manner, indicate one major orientation, N. 22°E., dipping 9° northeast. The two major orientations of the cooling faces are interpreted as reflecting the curvature of the outcrop, and the dip angle as reflecting the slope of the outcrop. Thus, the exposed outcrop surface represents the cooling surface. The columnals are nearly horizontal, and more or less perpendicular to the curving, cooling surface. The deviation from perpendicularity may be the result of non-random selection in sampling and the relatively small number of plotted columnal orientations. It is more likely, however, that it reflects the continuous curvature of the cooling surface. Outcrops at locations 14 and 23 also tended to show that the cooling surface was the curving exposed slope surface of the outcrop, and that the columnals were essentially perpendicular to the cooling surface. In those outcrops in which the horizontal top surface of the outcrop acted as the cooling surface, the perpendicular orientation of the columnals can easily be seen (Plate IX, Figs. 2 and 6).

A number of other fractures, not related to columnar jointing, were also plotted. In the case of the outcrop at location 15, three major systems were apparent. Two sets of fractures, N. 12°W., 0 dip, and N. 36°E., dipping 5° northeast, are interpreted as horizontal cracks resulting from vertical tension, which are secondarily influenced by bedding. The significance of the third fracture orientation, N. 82°E., dipping 25° southeast, is undetermined.

FOSSIL PRESERVATION

The occurrence of fossil leaves in "scoria" has received the attention of many investigators in the Little Missouri Badlands, since first recorded by Edward Harris in 1845 (p. 239). Small amounts of plant material may be found in the finer-grained "scoria" in most outcrops, but the outcrops of well-preserved leaves are relatively rare. Fragments of reed-like (?) plants (Equisetum ?) appear to be the most common fossil remains in "scoria". Woody stems and roots are also very common. Good leaf fossils were found, during the present investigation, in only five "scoria" outcrops, although a few well preserved leaves can be found in most outcrops. One of these outcrops, in which the fossil leaves show an exceptional state of preservation, is located in the SW¼ sec. 35, T. 140 N., R. 100 W. This outcrop, about three feet thick, is composed of a "mat" of leaves preserved in fissile "scoria". This small deposit would appear to have been an old bog which had eventually filled with plant detritus and fine silt.

Most of the plant fossils are preserved as impressions in the salmon pink, baked shale. Stems and woody material may be found in many varieties of "scoria". Fossilized leaves are very common in the limy clays and siltstones throughout the Tongue River Formation, and a few of these leaves are occasionally preserved in the metamorphosed equivalents, baked mudstones, baked shales, and porcellanite. These leaves are usually the best preserved of all fossils in "scoria". A few fruits (?) from Cercidiphyllum arcticum have also been recognized in the baked, salmon pink shale. Few plant fossils have been found in the coarser siltstones or in sandstones. Rocks of this coarseness probably indicate an environment of deposition unfavorable for the accumulation of plant material. It is also possible that the subsequent conditions for preservation in these coarse rocks were less favorable than those afforded by the finer sediments.

Numerous comments have been made in previous literature concerning the excellent preservation of fossil leaves in "scoria". In a general way this is true, as the leaf impression is usually rather sharply, and dramatically outlined against the pastel "scoria" background. Detailed investigation, however, usually discloses that the minimal identification criterion, veination, is not well preserved. Many impressions which would at first appear to be veins often are found to be either cracks or folds in the leaf. In many cases, even the margins of the leaves are indistinct. Only the following plants were definitely identified by the writer among several dozen relatively well-preserved specimens, Cissus marginata, Cercidiphyllum arcticum, Ficus artocarpoides, Metasequoia occidentalis, Corylus insignis, and Viburnum asperum. Stem (?) patterns, very similar to those of the fan palms (Brown, 1962, p. 54) were also common in some of the outcrops.

Tree limbs and stumps are occasionally preserved in "scoria". This type of plant material most often occurs in the "clinkerized" layer overlying the ash. It would appear that limbs, stumps, and fragments of wood may even contribute to the formation of "clinkerized" material. Some of this woody material has apparently become carbonized and indurated before burning took place, and upon ignition of the lignite became metamorphosed to "clinker"-like material. An especially interesting case of stump preservation in glassy slag was found in the NE¼NE¼sec. 14, T. 140 N., R. 104 W. The mass in which the stump had been preserved was composed of a glassy slag which had flowed, and appeared to have merely engulfed the stump in the molten condition. The transitional nature of the stump grading into the glassy slag would indicate, however, that the stump had been petrified before burning, and had later been metamorphosed to glassy slag. Some of the material in the center of the stump is strongly carbonized and rather poorly indurated. Thin sections of the metamorphosed stump show excellent preservation of the cell structure (Plate VII, Fig. 7). The glassy slag from this specimen also showed recrystallization.

Preserved animal fossils are relatively rare in "scoria". Only occasional fragments of terrestrial pelecypods and gastropods have been recognized. These fossils have been recognized only in the baked shales and porcellanites. The only outcrop in which these invertebrates are common is located in the NE¼sec. 27, T. 139 N., R. 102 W. This outcrop contains a large amount of porcellanite, in which a number of gastropods and a few pelecypod fragments are preserved.

USES FOR "SCORIA"

General Characteristics

"Scoria" is a resource which is abundant and widespread in occurrence over much of western North Dakota. Among the desirable attributes of "scoria" are availability, abundance, ease of development, and pleasing colors. This material is readily available over most of the area included within the "scoria line" (Fig. 1) in western North Dakota. "Scoria" is especially abundant in relatively continuous outcrop in the Badlands along the Little Missouri River, and locally, in the Glen Ullin area. As a result of the low bulk specific gravity of most varieties of "scoria", large volume payloads may be moved in light-duty hauling equipment. The development of "borrow pits" from "scoria" outcrops on the upland plain is especially easy. Most of these outcrops are at road height and only require the use of light-duty loading equipment (backhoes, front loaders, etc.) to develop the "borrow pit". Some outcrops may require the building of approach ramps before exploitation. As a result of intensive fracturing during metamorphism, "scoria" outcrops do not require explosives or breaking equipment to obtain the material from outcrop.

On the other hand, "scoria" has a number of undesirable characteristics which restrict its use. Among these are variability in outcrop, small size, large proportion of fines, low compression strength, low durability, high porosity, and tendency to stain. The single, greatest drawback to the widespread use of "scoria" is the great variation of material in outcrop. As earlier defined, "scoria" is composed of a number of varieties of metamorphic rock which have widely differing characters and physical characteristics. Most outcrops, even though they might appear to be dominantly of one variety of "scoria", typically have widely different varieties dispersed throughout the outcrop. This is particularly true of the thicker, more strongly metamorphosed outcrops. By the nature of their thickness, these outcrops are also the most desirable for development. Even the thicker outcrops which appear to be composed of baked shales typically contain layers of "clinker", glassy material, vitrified zones, areas of baked massive rock, and baked sandstone layers. The great diversity in character of "scoria" would usually require some method of sorting, detracting greatly from the use of this material in many marginal applications.

Intense fracturing during cooling has reduced most of the "scoria" to rubble, which immediately removes it from consideration as a dimension stone. Even the more massive blocks (baked siltstones, baked sandstones, and porcellanites), rarely attain dimensions greater than several square feet. These blocks are usually incipiently fractured and have poor shock and compressive strength.

The low compression strength, low durability, and high porosity all contribute to the continued breakdown of "scoria", producing an excessive amount of fine material, both in the outcrop and in use. The high porosity permits excessive expansion and contraction of water-ice in the interstices during thawing and freezing, thereby breaking down the rock and contributing to low durability. In the outcrop, the excessive production of fines would generally require screening for many applications. In use, the rather rapid breakdown and low durability of "scoria" detracts greatly from utilistion in permanent applications. The tendency towards excessive formation of fines also may be objectionable. The formation of pervasive red dust and stain tends to detract from the utilization of this material where a "clear" material is required.

<u>Road Metal</u>

"Scoria" has found its greatest application as road metal for secondary roads. Large amounts of this material are used throughout the western part of North Dakota for this purpose. This road metal makes a very attractive, well-drained, light-duty road, and it is regrettable that these scenic roads have not been retained in the Theodore Roosevelt National Memorial Park. On the other hand, maintenance requirements of these roads under the heavy travel conditions of summer traffic have been excessive. The baked shales, which are normally used, provide a well-drained surface, but tend to pack poorly, and break down easily. Poor packing and break-down are both caused by the shaly fracture common to this variety. Poor durability is a result of low freeze and thaw resistance, which is related to the high porosity. Porcellanite and vitrified siltstones make the best road metal due to their angularity (good packing), durability (low porosity), relatively high compression strength, and abrasion resistance. Unfortunately, however, these varieties are not particularly abundant in any one outcrop, and are usually intermixed within the outcrop. Glassy varieties are also rare and are reportedly hard on tires.

Recent, limited studies by members of the North Dakota Highway

Department (personal communication, 1963) have indicated that "scoria" may still have a bright future as paving material. In studies by the same agency (written communication, 1963) on the stabilization of western aggregates, it was found that "scoria" could be dramatically improved as a lightweight aggregate by standard stabilization treatment. The tests were performed on a single specimen of "good grade 'scoria'" (apparently a baked shale), and are presently considered tentative. The specimen was treated with lime, cement, and emulsified asphalt. "Scoria" failed completely when treated with emulsified asphalt, but showed interesting improvement with cement and, especially, lime treatment. As "scoria" does not have a plasticity index it has an immediate advantage over other lightweight aggregates. This lack of plasticity means that compactive effort for "scoria" aggregate will not be so great as is necessary for plastic materials in base and subbase applications. Addition of lime provided a surprising increase in hardness, strength and durability of "scoria". Highway Department tests of raw "scoria" indicated an unconfined compressive strength of 84 psi. However, when treated with nine per cent lime, the same specimen tested 232 psi with a maximum dry density of only 92.3. The conclusion was that "scoria" produced a higher strength than the seven other heavy aggregates tested, with less lime. "Scoria"-lime mixtures also gain strength during freeze-thaw cycles similar to gains made by heavy aggregates. According to North Dakota Highway Department investigations (written communication, 1963), after five cycles of wetting and drying the nine per cent lime-"scoria" mixture was oven-dried and tested at 700 psi compression strength. The mixture also resisted dry aggregate loss by brushing during freeze-thaw and wet-dry tests as well as other heavy aggregates tested. Moisture absorption was less than three per cent for the mixture during 24 days of absorption. From this series of tests the Highway Department investigator, Alan Huseth (written communication, 1963), concluded that "scoria" was improved by the addition of lime more than any other aggregate tested. He also suggested that partial substitution of lignite fly-ash for lime might also produce the same results with lower cost.

Cement mixtures also produced similar improvements in "scoria". The addition of cement, however, increases the specific gravity of the mixture, somewhat reducing its advantage as a lightweight aggregate. The following requirements are often accepted for strength of strong base and subbase materials.

7 days moist cured	100 to 300 psi
7 days moist cured; then oven dried	500 psi
For resistance to frost:	
7 days moist cured	300 to 500 psi

It should be noted, however, that Huseth (written communication, 1963) considers the strength necessary for resistance to frost to be excessive. A four per cent cement mixture (by weight) was sufficient to provide these strengths in "scoria", a strength-mixture ratio which was equaled by only one other aggregate tested. This same mixture also produced the greatest gain in strength during the freeze-thaw test. It further showed a "remarkable" increase during 24 days of swell-absorption, and did not swell at all. It may be concluded from the results of this report that "scoria" could play a large role in future road building in western North Dakota.

The lime tests also indicate that "scoria" has interesting pozzolan properties. It is possible that further investigation of this resource in connection with low grade lime sources from the Niobrara Formation, and lignite fly-ash might lead to the production of a low grade, low cost, cement product for the expanding puzzolan cement and lightweight aggregate market.

According to Hares (1928, p. 58), "scoria" has also been utilized as railroad ballast through areas in which the material occurs. He has also stated that, in Nebraska, many of the railroads have produced similar material artificially for use as ballast. "Scoria" is not presently being used for ballast in North Dakota, and it is unlikely that any of the raw "scoria" would meet the present standards for this material. As ballast standards are similar to those for road metal, however, it is probable that lime or cement treated "scoria" could be used to provide a well-drained roadbed.

"Scoria" has also found considerable use for oil well access roads. This is apparently due to availability, but the oil absorption characteristics of baked shale provide an unexpected bonus, when utilized for this purpose. It is suggested that baked shales would provide a desirable surface where oil waste accumulates. This material should provide a good traction surface, even when nearly saturated with oil.

Building Stone

The general characteristics of "scoria" severely restrict its application as a building stone. Some of the more compact and massive varieties (porcellanites, vitrified siltstones), might be used to relieve the monotony of masonary walls, but the durability of most varieties would limit widespread masonary applications for exterior use.

The possibility of iron-staining must be considered in the use of some varieties of "scoria" for exterior use. The attractive color and even grain of selected varieties also make attractive decorative stone for interior use, especially where durability is not a prime factor.

Perhaps the second greatest application of "scoria" has been in roofing. The reddish, baked shales make a pleasing, storm-proof, relatively light weight roof covering. This covering was specified, for appearance, as a veneer over pea gravel on the roof of the lecture bowl of the geology building (Leonard Hall) at the University of North Dakota. "Scoria" coverings are also used without a binder on many secondary ranch and farm buildings in western North Dakota. This material provides low cost, hail and wind-proof coverings for these lean-to roofs. The baked shale usually requires only slight sorting to remove fines and large blocky pieces.

The bright colors of baked shale, its platy fracture, and the increased, strength and durability characteristics when combined with small amounts of cement suggest that this material could be embedded in cement to form an attractive, non-slip, exterior terrazzo. Although the material generally will not polish it is probable that the abrasive surfaces would be desirable for non-slip applications (swimming pools, patios, etc.). Larger pieces of "scoria" might be used to provide a "flaggy" effect.

Ceramics

"Scoria" is presently being used for a texturing effect in some brick manufacture at the Hebron Brick Company, Hebron, North Dakota. This brick has a very attractive, rugged, "natural" appearance. It is prepared by adding about 30 per cent "scoria", which has been ground to 5 mesh size. The ceramics engineer, Virgil Rogers (personal communication, 1963), is presently experimenting with other mixtures to determine different texturing effects. It is expected that the best mixture will be provided by using less "scoria" ground to a finer size.

It is also very possible that some ground "scoria" could also provide an interesting texturing effect when used in the fashion of stucco. Another possibility would be facing of concrete block to provide a natural stone appearance. According to Prof. Pachl (personal communication, 1965) "scoria" has also been used for a texture and grog effect in some ceramics produced in the Ceramics Department of the University of North Dakota.

"Scoria" has characteristics which would enable it to be used as a grog in dimension brick. Grog is pre-fired, pre-shrunk material which aids in drying, decreases plasticity, and maintains dimension of fired ware. It might be used in brick making, but the large supply of broken and rejected brick is usually used for this purpose. "Scoria" has also been used as grog in the manufacture of sewer pipe at the Dickinson Sewer Pipe Works, Dickinson, North Dakota, but according to the owner (personal communication, 1962), "'scoria' tended to produce an ash when fired, which left cavities, and might cause breakage in freezing weather". It would appear to the writer, however, that this is mainly a matter of selection, as some varieties would definitely not fire with production of an ash. With expanding need for brick and fired dimension clayware, "scoria" may find increased use in this field.

Alumina and Phosphate Protore

In 1961, Dismant proposed the possibility that some varieties of "scoria" might be a potential major source of economic alumina production. He based this suggestion on the theory that metamorphism of "scoria" had already accomplished the calcining process necessary to render the aluminous compounds in the low grade clays soluble in acids or alkalies. According to Dismant (1961, p. 18), "scoria" could provide a savings of from 10 to 35 per cent over low grade clays (15 per cent alumina) which would have to be calcined. Hansen has reported (1959, p. 4), that the Tongue River Formation clays generally contain from 10 to 15 per cent alumina, and that the minimal economic recovery content should be at least 20 per cent. "Scoria" is presently being studied by Dr. J. A. Stewart of the Chemistry Department at the University of North Dakota as a possible source of alumina along with low-grade clays. According to Stewart (written communication, 1965), preliminary investigation indicates that "some samples of scoria appear to have an unknown (physical or chemical) factor which makes them more susceptible to acid extraction".

It must be remembered, however, that these admittedly marginal prospects require very abundant supplies of protore which generally must be treated at a localized plant. While "scoria" is reasonably abundant, it generally occurs in scattered outcrops which would require the use of mobile collecting and grading plants. It is also unlikely that the glassy and vitrified varieties would be usable, or at least, treatable by the same "flow" process. This would mean that a sorting plant might be necessary, further adding to preparation costs. It is also debatable whether easily obtainable, abundant supplies of "scoria" could be secured over a reasonable working-recovery area. The crushing costs of "scoria" would also offset some of the advantages of "natural" calcining over low-grade clay processing.

Baked and melted sediments similar to "scoria" have recently been prospected as a source of phosphate in California (Lydon, 1964). Some of these baked sediments contained as much as 20 per cent phosphate (P_2O_5). Phosphate in the California material is contained in the minerals apatite, hydroxyapatite, and whitlockite. The source of this mineralogy has not yet been determined. It is interesting that a few specimens of baked shale and glassy slag collected by the writer also showed a positive test for phosphorous. A chemical spot test for phosphorus may easily be performed by placing a small amount of finely ground ammonium molybdate on the rock surface and adding a few drops of nitric acid; if the rock contains phosphorous, a bright yellow color appears within about one minute (Lydon, 1964, p. 66). The sediment and resulting "scoria" are known to contain apatite, but this mineral appears to compose less than one per cent of the rock or sediment. No other phosphatic minerals were identified in the present study. The writer would suggest in the light of this new development, that future studies of "scoria" should include a prospecting program for phosphorus. There would appear to be a good market for phosphate rock as a fertilizer, and as a stock feed supplement, if this compound should prove economically recoverable.

<u>Miscellaneous Uses</u>

The evenly distributed pore space, good drainage, and rough surface characteristics of baked shales should make this material an excellent filter bed. It is believed that this material should have desirable characteristics for water drains, and sewage filter beds. The rough surface of the baked shale should provide good lodging places for bacteria which by their life processes effect purification of sewage. Fines must be separated out for this use.

Most of the reddish colored "scorias" have a very permanent, and regular, pervasive color when finely ground. It is probable that this finely ground material might be used as a low cost coloring agent and pigment in some applications. It is also possible that less finely ground material might be used as a distinctive line marker on athletic fields.

Another possibility for the use of "scoria" chips might be as a colorful additive for bulb growing and rock gardens in the expanding home garden trade. This type of material has also been used in soil conditioning.

Some "scoria" has also been sold locally as a vacation souvenir from the Little Missouri Badlands.

SUMMARY OF CONCLUSIONS

Although, occasionally misinterpreted, the origin of the metamorphic rock, "scoria", has been known since the early investigations of Lewis and Clark. In fact, their observations were little improved upon for the next 70 years. Since that time, numerous observations on these peculiar deposits appeared, but it was not until 1918 that the first systematic work appeared. "Scoria" has received only limited study since this time.

The most likely cause for widespread and recurring ignition of lignite in the outcrop is spontaneous combustion, even though rare occurrences of ignition from other causes are known. The mere burning of lignite under oxidizing conditions beneath overburden, however, is not sufficient to produce thick or strongly metamorphosed "scoria". Neither the composition of the parent sediments, nor the composition or grade of the lignite in two presently burning areas, is significantly different from the sediments and lignites which have formed "scoria" in the past. It is evident, therefore, given suitable sediments and lignite, that the formation of "scoria" is most dependent on the thickness and competence of overburden. Thick and strongly metamorphosed "scoria" is formed only when the overburden is sufficiently thick to restrict eventually the access of air to caverns in the underlying, burning lignite, causing reducing conditions. The large deposits of melted "scoria", and "chimneys" form when overburden fractures, and combustion gases produced in a distilling atmosphere combine at a rapid rate of reaction with inrushing air. Outcrops of extremely thick "scoria" are produced by the burning of several seams or stringers of lignite.

Over-simplification and generalization have hindered the understanding of the conditions and modes of formation of "scoria". Various combinations of conditions lead to four modes of formation of "scoria". The general diversity of varieties of "scoria" has generally not been appreciated. The present study distinguishes at least nine varieties. Previous generalizations concerning lignite-ash-"scoria"-overburden relationships are usually valid only when applied to burning in a strongly oxidizing environment. These relationships are more related to the conditions of formation and efficiency of burning, than to comparative thicknesses of lignite, ash, overburden, and "scoria".

The general effects of "scoria" on topography are the preservation of buttes and ridges capped by "scoria", and the retardation of erosion of slopes covered by "scoria" talus. Overall orientation of jointing in "scoria" bears a general relation to dissection in the area, but pseudocolumnar jointing is controlled by the orientation of the cooling surface. Individual columnar joints often deviate from the simple, theoretical, hexagonal pattern, and appear to be influenced by a combination of other factors.

Deposits of "scoria" represent a widespread, abundant, and valuable resource in North Dakota. The possibilities for utilization of this valuable and varied resource have barely been explored.

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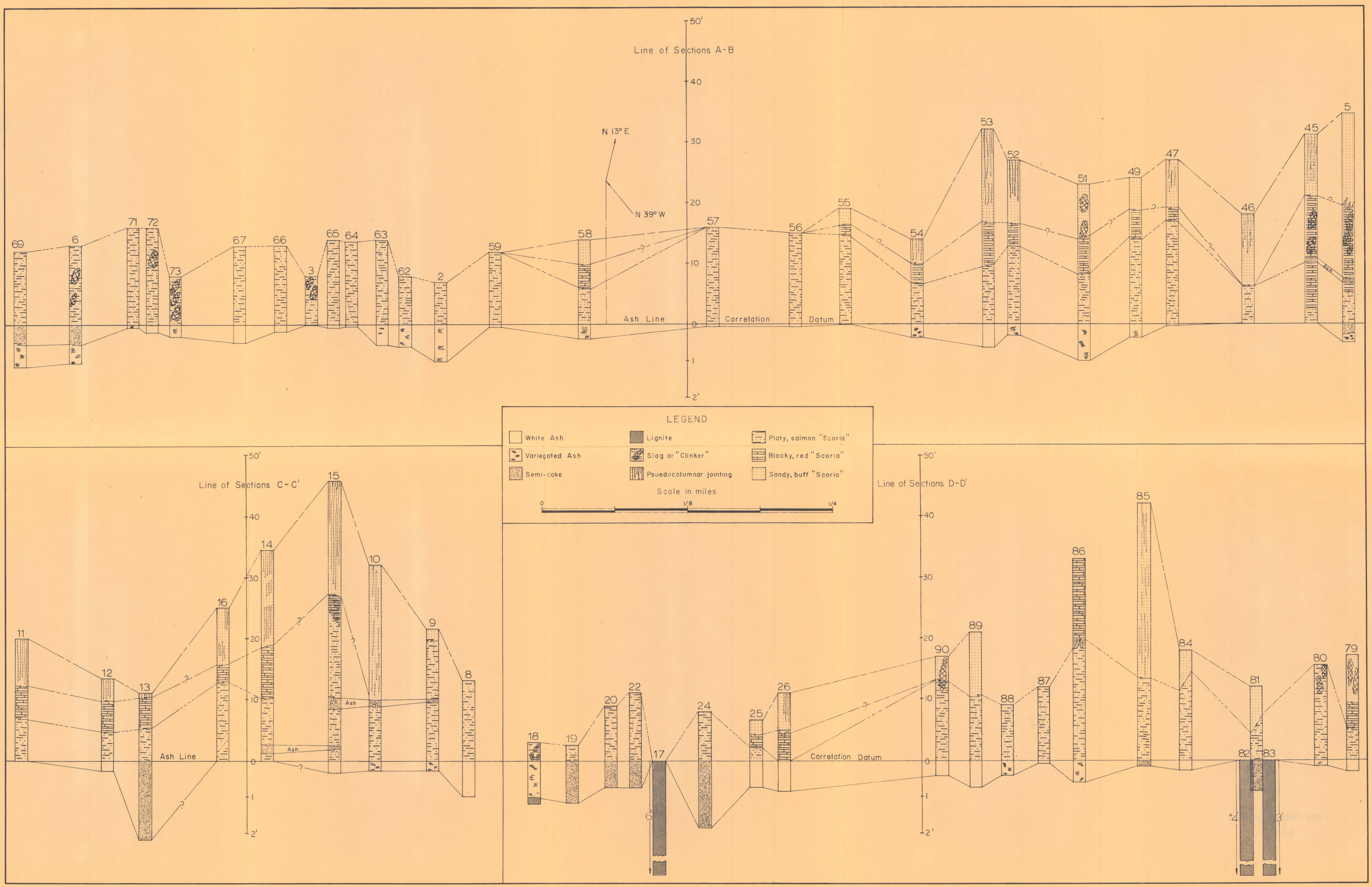

Line of Sections A-B
N 13° E
N 39° W
Ash Line
Correlation
Datum
LEGEND
White Ash
Variegated Ash
Semi-coke
Lignite
Slag or "Clinker"
Psuedocolumnar jointing
Platy, salmon "Scoria"
Blocky, red "Scoria"
Sandy, buff "Scoria"
Scale in miles
0
1/8
1/4
Line of Sections C-C'
Ash Line
Ash
Line of Sections D-D'
Correlation Datum


Line of Sections F-F'
128
126
127
125
129
122
121
124
123
120
119
118
117
116
50'
40
30
20
10
0
1
2'
Ash Line
Correlation
Datum
Line of Sections F-F' continued below
LEGEND
White Ash
Variegated Ash
Semi-coke
Lignite
Slag or "Clinker"
Psuedocolumnar jointing
Platy, salmon "Scoria"
Blocky, red "Scoria"
Sandy, buff "Scoria"
Scale in miles
0
1/8
1/4
Line of Sections F-F' continued from above
116
115
114
113
112
111
110
109
108
107
106
105
104
134
152
151
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